

<sup>114</sup>  
*The Journal of the*  
**INSTITUTE OF**  
**METALS**

*and*  
**METALLURGICAL ABSTRACTS**



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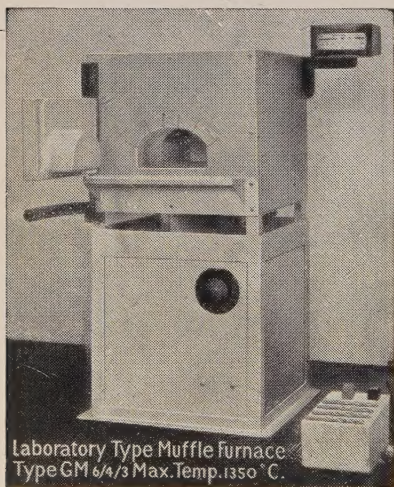
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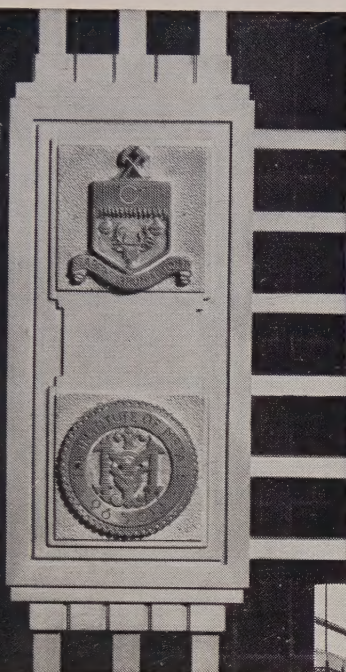
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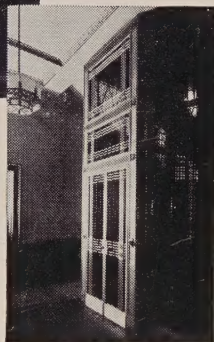


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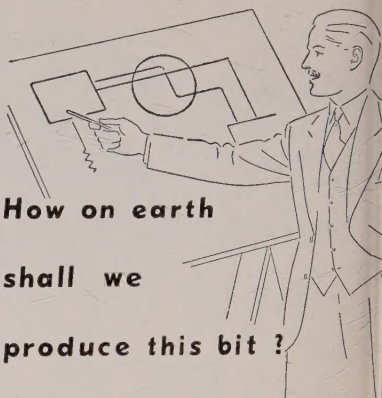


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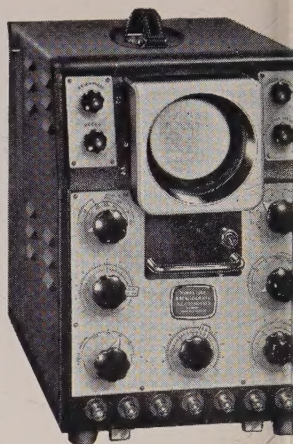
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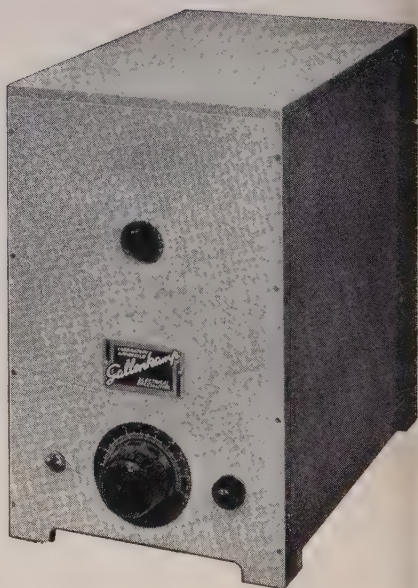
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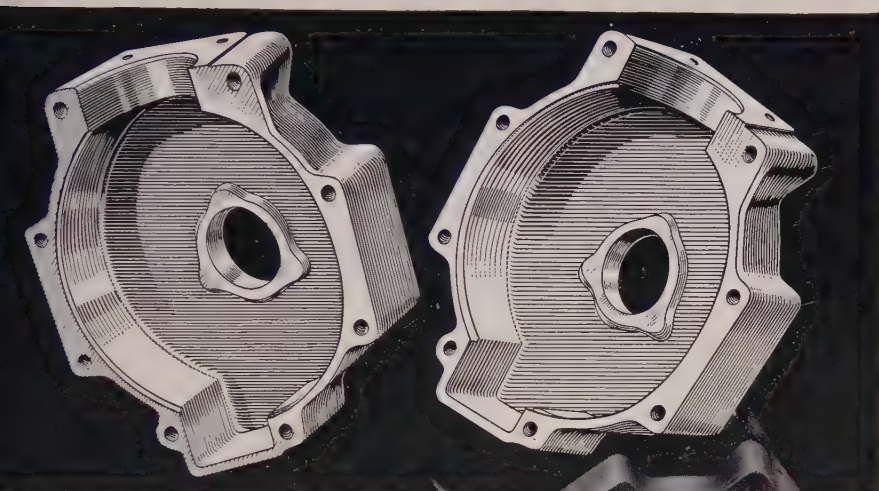


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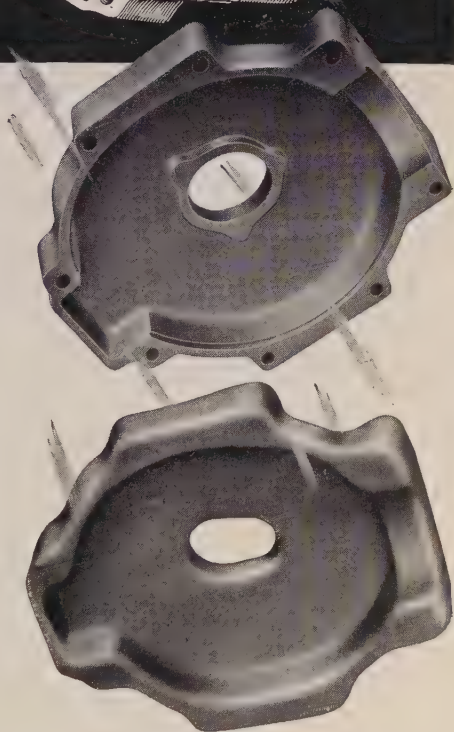


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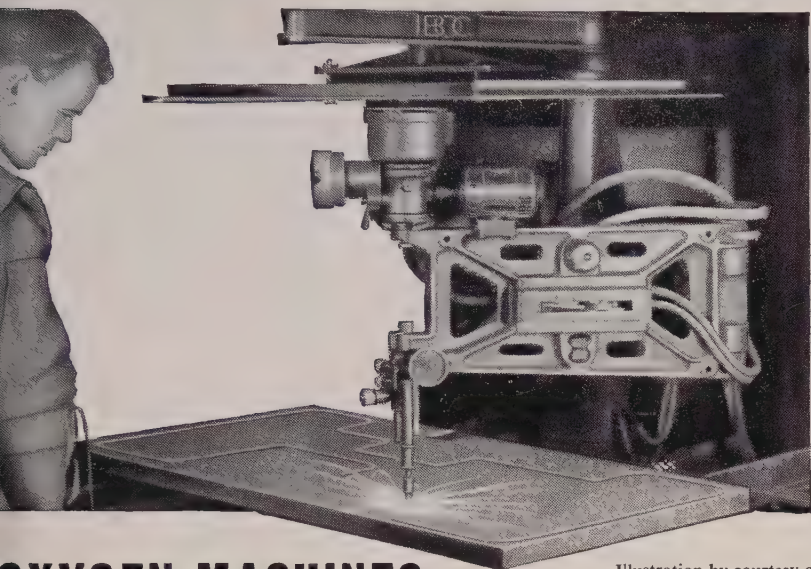


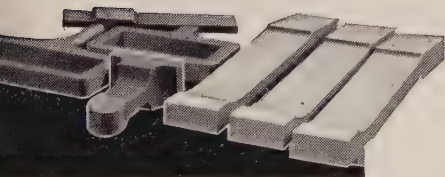
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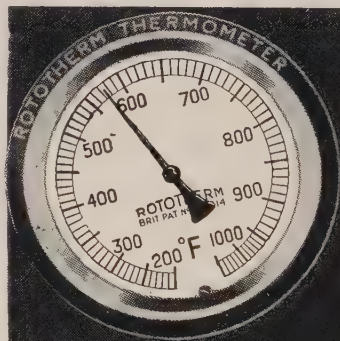
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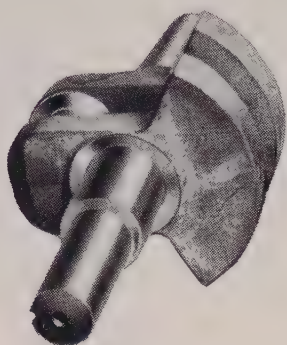
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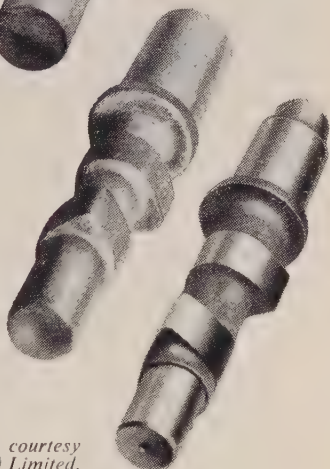


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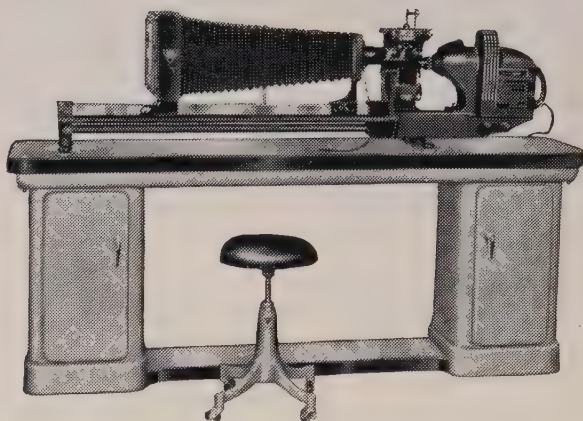
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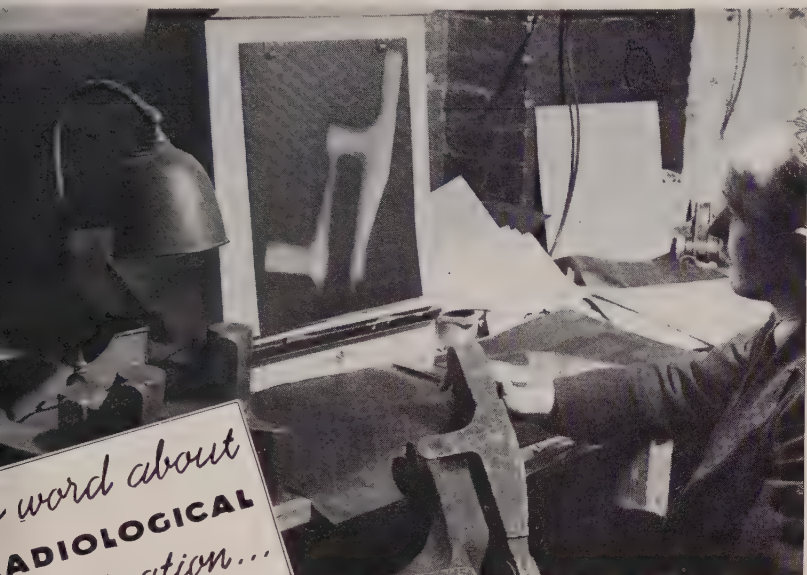
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# JOURNAL OF THE INSTITUTE OF METALS

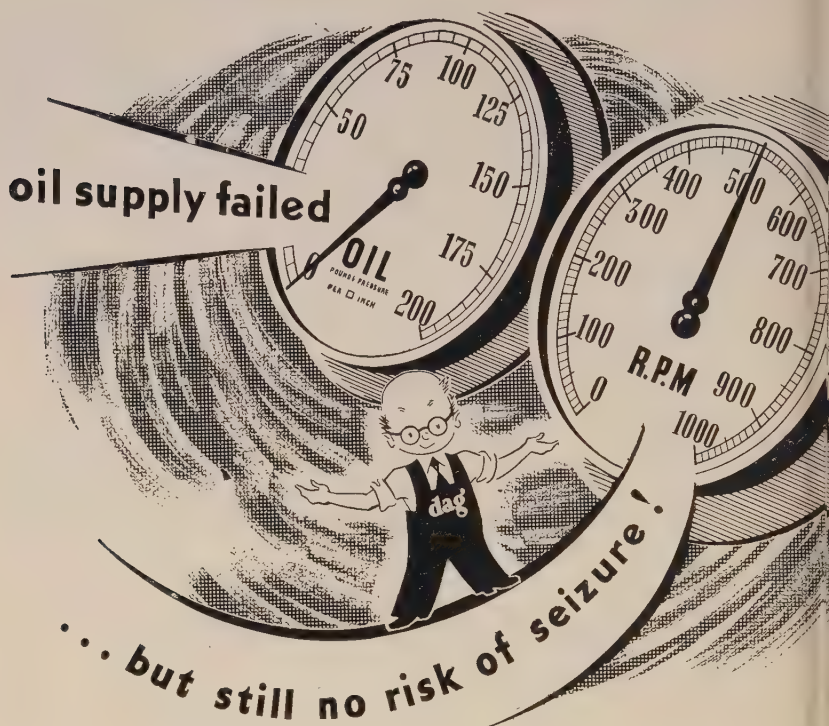
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July 1948.

# THE INSTITUTE OF METALS

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## LETTER TO THE EDITOR

### PRACTICAL PAPERS

SIR,

Sir Arthur Smout in his Presidential Address drew attention to the old complaint that the Institute has difficulty in attracting a reasonable proportion of so-called "practical" papers. Those members who are engaged in productive industry have not the same incentive to write papers as others who are scientific researchers. Another difficulty is that the Institute cannot easily approach individuals to send papers on specified subjects without committing itself to publish the papers, whether good or bad.

It has recently seemed to me that the issue, from time to time, by the Publication Committee of a list of topics for such papers might be much more effective than just asking for "practical papers".

The present critical position of our country, and the need for increased productivity, justifies the pooling of technical knowledge, and even secrets, at least as strongly as any previous war period. It would be particularly welcome, therefore, to see some papers with reports of how a progressive firm has tackled an old process, run on traditional lines, and, by modernizing it, has reduced costs. Whereas our constitution precludes us from dealing with Trade Union matters, it certainly does nothing to discourage the presentation of papers on production costs.

In the hope that others will submit additions to the list, I venture to put forward a few titles, papers on which would be welcome :

Old and Modern Shop Layout : Effects of Modernization.

Metal Polishing.

Metal Spinning.

Decorative Colouring of Metals.

Brazing and Silver Soldering.

Analytical Control : Aluminium Alloys.

Analytical Control : Copper or Brass.

Requisites for Superfinished Surface of Strip Metals.

Bright Annealing.

Scrap Recovery and Reclamation.

Yours faithfully,

**R. S. HUTTON.**

*Cambridge,  
9 June 1948.*

The Editor will be pleased to receive correspondence on the subject of this letter.

## INSTITUTE NEWS AND ANNOUNCEMENTS

### AUTUMN MEETING, CAMBRIDGE, 14-17 SEPTEMBER 1948

As previously announced, the Autumn Meeting of the Institute will be held in Cambridge from Tuesday, 14 September, to Friday, 17 September 1948, and the Council hopes that there will be a large attendance. Many members from overseas are known to be intending to be present.

A full programme, with reply form, will be sent to all members in July, and it is particularly requested that those who propose to be present shall complete and return the reply forms at their very earliest convenience.

#### PROGRAMME

##### Tuesday, 14 September

- 2.0-6.0 p.m.—Secretary's office, and lounge for members and their ladies, will be open at the Arts School.
- 6.30 p.m.—Service in the Church of St. Edward, King and Martyr; sermon by the Vice-Chancellor of the University (Rev. Canon C. E. Raven, D.D.).
- 8.0-11.0 p.m.—Conversazione in the Old Schools. There will be music and light refreshments, and also an exhibition of scientific apparatus and instruments by the Cambridge Instrument Co., Ltd., and by Unicam Instruments (Cambridge), Ltd., and displays of scientific and technical books by the Cambridge University Press, Messrs. Bowes and Bowes, Ltd., and Messrs. W. Heffer and Sons, Ltd.

##### Wednesday, 15 September

- 9.0 a.m.—12.45 p.m.—Secretary's office, and lounge for members and their ladies, open at the Arts School.
- 9.45 a.m.—12.30 p.m.—Meeting in the Arts School.  
Welcome by His Worship the Mayor of Cambridge.  
Brief business meeting.  
Discussion on "The Micro-Hardness Testing of Metals", based on a paper by E. Wilfred Taylor (June 1948).  
Presentation and discussion of a paper by G. A. Cottell, K. M. Entwistle, and F. C. Thompson on "The Measurement of the Damping Capacity of Metals in Torsional Vibration" (March 1948).
- 12.45 p.m.—Luncheon at the Dorothy Café (tickets, 6s.).
- 2.0 p.m.—Visits for members to :
- (1) (a) Metallurgical Laboratories of the University; and (b) Mineralogical Department; or (c) Scott Polar Research Institute.
  - (2) Engineering Laboratories of the University.
  - (3) Cambridge Instrument Co., Ltd.
  - (4) (a) Pye, Ltd., and (b) Unicam Instruments (Cambridge), Ltd. (charge for transport, 3s.).

## NEWS AND ANNOUNCEMENTS

Visits for members and ladies :

- (5) Conducted tour of the Colleges.
- (6) Low-Temperature Research Station (D.S.I.R.).
- (7) Fitzwilliam Museum.
- (8) Botanical Gardens.

7.0 p.m.—midnight.—Supper-Dance at the Guildhall (tickets, 21s.).

### Thursday, 16 September

9.0 a.m.—12.45 p.m.—Secretary's office, and lounge for members and their ladies, open at the Arts School.

9.45 a.m.—Meeting in the Arts School.

Presentation and discussion of papers :

J. S. Bowles and W. Boas on "The Effect of Crystal Arrangement on 'Secondary Recrystallization' in Metals" (June 1948).

Maurice Cook and T. Ll. Richards on "Observations on the Annealing Characteristics of an Aluminium-Copper-Magnesium Alloy" (July 1948).

12.45 p.m.—Luncheon at the Dorothy Café (tickets, 6s.).

2.0 p.m.—Visits for members to :

- (1) Cavendish Laboratory (at which there will also be an exhibition of the work of Dr. F. P. Bowden and his colleagues), and the Royal Society Mond Research Laboratories.
- (2) Research Laboratories of the British Welding Research Association, Abington (charge for transport, 3s.).
- (3) Aero Research, Ltd., Duxford (charge for transport, 3s.).

Visits for members and their ladies :

- (4) Cambridge University Press.
- (5) Conducted tour of the Colleges.
- (6) Fitzwilliam Museum.
- (7) Botanical Gardens.

6.0 p.m.—Autumn Lecture, at the Arts School, by Professor Sir Lawrence Bragg, O.B.E., M.C., Sc.D., LL.D., F.R.S., Hon.M.Inst.Met., on "The Cavendish Laboratory".

*Note :* Dinner will be arranged (if desired) for individuals or parties, at the University Arms Hotel, after the lecture and not later than 8.0 p.m.

### Friday, 17 September

10.0 a.m.—All-day visits (returning to Cambridge) for members to the works of :

- (1) W. H. Allen, Sons and Co., Ltd., Bedford (charge, 17s. 6d., inclusive of lunch, transport, and gratuities).
- (2) Manganese Bronze and Brass Co., Ltd., Ipswich (charge, 15s., inclusive of lunch, transport, and gratuities).
- (3) W. H. A. Robertson and Co., Ltd., Bedford; lunch by invitation of the Directors (charge for transport, 7s. 6d.).



## NEWS AND ANNOUNCEMENTS

- (4) Stewarts and Lloyds, Ltd., Corby; lunch by invitation of the Directors (charge for transport, 10s. 6d.).

All-day visit (returning to Cambridge) for members and their ladies to:

- (5) Peterborough and Ely Cathedrals, lunching at Peterborough and returning via Newmarket (charge, 17s. 6d., inclusive of lunch, transport, and gratuities).

### Accommodation

Accommodation has been reserved, for the nights of 14, 15, and 16 September, at hotels in Cambridge, at Trinity Hall (by kind permission of the Master), and at University lodgings. Full particulars are given in the programme circulated to all members.

### Registration Fee

A registration fee of 10s. 6d. will be charged to all members attending, to cover the cost of the conversazione, badge, and administrative expenses; no fee will be charged in the case of members' ladies.

### WORKS TOUR FOR STUDENT MEMBERS, EASTER VACATION, 1949

The Council has made arrangements for a tour of works in Birmingham, for Student Members of the Institute, to take place from 4 April to 8 April 1949, inclusive. Accommodation has been arranged, and the cost of the tour will be kept as low as possible.

Full particulars will be sent to all Student Members in the autumn.

### ELECTION OF COUNCIL

In accordance with the Articles, the following are due to retire from the Council at the 1949 Annual General Meeting:

#### *President :*

Sir Arthur Smout, J.P.

#### *Vice-Presidents :*

Professor G. Wesley Austin, O.B.E., M.A., M.Sc.  
W. F. Brazener, J.P.

#### *Ordinary Members of Council :*

Major C. J. P. Ball, D.S.O., M.C.  
L. B. Pfeil, O.B.E., D.Sc., A.R.S.M.  
C. J. Smithells, M.C., D.Sc.

The President is eligible for re-election. The Vice-Presidents are not eligible for re-election except as President or Honorary Treasurer, and the Ordinary Members of Council are not eligible for re-election except as President, Honorary Treasurer, or Vice-President, until the lapse of one year after their retirement. (There is no vacancy for election as Honorary Treasurer.)

In accordance with Article 22, the Council nominates the following members to fill the vacancies:

## NEWS AND ANNOUNCEMENTS

### *As President :*

SIR ARTHUR SMOUT, J.P., Director, Imperial Chemical Industries, Ltd., London ; Director, Murex, Ltd., Rainham ; Director, Magnesium Elektron, Ltd., Manchester ; Director, Pyrotenax, Ltd., Hebburn-on-Tyne ; Member of Council, British Non-Ferrous Metals Research Association.

### *As Vice-Presidents :*

MAJOR C. J. P. BALL, D.S.O., M.C., Chairman and Managing Director, Magnesium Elektron, Ltd. ; Managing Director, F. A. Hughes and Co., Ltd. ; Director, Sterling Metals, Ltd.

C. J. SMITHELLS, M.C., D.Sc., Director of Research, The British Aluminium Co., Ltd., Gerrards Cross.

### *As Ordinary Members of Council :*

E. A. BOLTON, M.Sc., Factory Manager, Imperial Chemical Industries, Ltd., Metals Division, Birmingham.

C. H. DAVY, Director, Babcock and Wilcox, Ltd., London.

A. G. QUARRELL, D.Sc., Ph.D., A.R.C.S., D.I.C., Research Manager, British Non-Ferrous Metals Research Association, London.

Members are reminded that, in accordance with Article 22, any ten members may also, at or before the Autumn General Meeting (14-17 September 1948), nominate in writing, with the written consent to act if elected of the person nominated, any duly qualified person other than one of those nominated by the Council to fill any vacancy on the Council, but each such nominator is debarred from nominating any other person for the same election. If two or more persons are nominated for any honorary office they (or such of them as are not ordinary Members of the Council who are not retiring at the next Annual General Meeting) will be deemed to have been nominated also for any vacancies among the ordinary Members of Council. No person is eligible to fill any vacancy at such Annual General Meeting unless he has consented in writing to be nominated and has been nominated or deemed to be nominated for the same in compliance with this Article.

---

## ELECTION OF ORDINARY MEMBERS AND STUDENT MEMBERS

The following 38 Ordinary Members and 13 Student Members were elected on 15 June 1948 :

### *As Ordinary Members*

ANDRADE, Professor Edward Neville da Costa, D.Sc., Ph.D., F.R.S., Quain Professor of Physics, University College, Gower Street, London, W.C.1.

AUSTIN, James Bliss, Ch.E., Ph.D., Director of Research, United States Steel Corporation, Kearny, N.J., U.S.A.

BARRY, Frederic Martin, Ph.B., M.S., Chief Chemist, Scovill Manufacturing Company, Waterbury, Conn., U.S.A.

BENARD, Jacques, Maître de Conférences à la Faculté des Sciences de Lyon, 93 rue Pasteur, Lyon, France.

## NEWS AND ANNOUNCEMENTS

- BERGER, Ollie J., Sr., Ollie J. Berger Company, Mill Representatives, 139 N. Clark Street, Suite 609, Chicago, Ill., U.S.A.
- BLAKEY, Professor Othman Frank, M.E., Professor of Civil Engineering and Dean of the Faculty of Engineering, University of Western Australia, Nedlands, W.A., Australia.
- BRENNER, Victor, Director, Deutsch and Brenner, Ltd., Alliance Works, Harford Street, Birmingham 19.
- BURGERS, Professor Wilhelm Gerard, Dr.Chem., Professor of Physical Chemistry, Laboratorium voor Physische Chemie, Technische Hoogeschool, 136 Julianalaan, Delft, Holland.
- CAMPBELL, Donald Le Strange, M.C., Metallurgical Engineer, Electric Furnace Company, Ltd., Netherby, Queen's Road, Weybridge, Surrey.
- CANEPA, Professor Dr. Francisco Guido, Chem. Eng., Assistant Professor, Chemical Engineering School, Universidad de Concepción, Casilla 169, Concepción, Chile.
- CRITCH, Colonel Jerry M., B.S., M.M.E., Director, Research and Development, American Car and Foundry Company, 30 Church Street, New York 8, N.Y., U.S.A.
- DIBLEY, Cornelius, Works Metallurgist, A. and G. Price, Ltd., P.O. Box 24, Shames, New Zealand.
- GRUENFELD, Ernst, B.Sc., Director and Works Manager, London and Scandinavian Metallurgical Company, Ltd., Marlborough Works, Chippinghouse Road, Sheffield.
- HAMILL, Harold L., A.B., B.S., City Librarian, Los Angeles Public Library, 630 West 5th Street, Los Angeles 13, Cal., U.S.A.
- HARPER, Henry Graham, Chief Metallurgist, Vickers-Armstrongs, Ltd., Crayford Works, Crayford, Kent.
- HICKMAN, Edwin Norman, A.B., Vice-President, American Metal Co., Ltd., 61 Broadway, New York 6, N.Y., U.S.A.
- HURDMAN, William Lawson, M.Sc., Director and General Manager, Parkinson Stove Company, Ltd., Stechford, Birmingham.
- KAMM, Robert, A.B., M.A., D.Sc., Senior Lecturer in Physical Metallurgy, School of Metallurgy, Melbourne University, Melbourne N.3, Vic., Australia.
- LUMSDEN, John, B.Sc., Chemist, Research Department, National Smelting Company, Ltd., Bristol.
- MCMASTER, James Gordon, B.Sc., Lecturer in Metallurgy, Department of Chemical Engineering, University of Sydney, Sydney, N.S.W., Australia.
- MAHIN, William Edward, M.S., Chairman, Metals Research, Armour Research Foundation, 35 W. 33rd Street, Chicago 16, Ill., U.S.A.
- MARZKE, Oscar T., Sc.D., Superintendent, Metallurgy Division, Naval Research Laboratory, Washington 20, D.C., U.S.A.
- NASH, William F., Jr., Ph.D., Metallurgy Consultant, C. F. Braun and Company, 1000 South Fremont Avenue, Alhambra, Cal., U.S.A.
- NAVARRO, José, Chief of the Foundry Department, Iron and Steel Institute of Spain, Calle Tutor 45, Madrid, Spain.
- PLATT, Sydney William, Chairman and Managing Director, John Walton and Company (Castleside), Ltd., Metalex Works, Great Cambridge Road, Enfield, Middlesex.
- QUIGLEY, Arthur H., President, American Brass Company, 414 Meadow Street, Waterbury, Conn., U.S.A.



## NEWS AND ANNOUNCEMENTS

- ROBERTS, Archibald Lewis, Chief Chemist, Sentinel (Shrewsbury), Ltd., 4 Victoria Street, Shrewsbury.
- ROSSI, Irving, Engineer, Rossi Continuous Casting Company, 17 John Street, New York 7, N.Y., U.S.A.
- SALÍS, Manuel, Civil Engineer, Soc. Esp. de Construcciones Electro Mecánicas, Calle Alcalá 16, Madrid, Spain.
- SCHNEIBLE, James H., B.S., Chief Metallurgist, Reynolds Alloys Company, Listerhill (Sheffield), Ala., U.S.A.
- SCHWAB, Harry Gustav, B.S., Chief Metallurgist, Bunting Brass and Bronze Company, 715 Spencer Street, Toledo 9, O., U.S.A.
- SNOWDEN, Edward Walter, General Manager, James Bridge Copper Works, Ltd., Darlaston Road, Walsall, Staffs.
- SUMNER, Edwin Vose, IV, S.B., Metallurgist, American Smelting and Refining Company, Federated Metals Division, 4010 E. 26th Street, Los Angeles, Cal., U.S.A.
- TSCHUDNOWSKY, Jean-Roger, Ing. civil Mines, Directeur technique de la Compagnie Générale du Duralumin et de Cuivre, 23/25 Avenue Franklin D. Roosevelt, Paris (8e), France.
- UNDERWOOD, Leslie Reneson, D.Sc., Ph.D., A.C.G.I., Chartered Mechanical Engineer, W. H. A. Robertson and Company, Ltd., Lynton Works, Bedford.
- VANDERPLOEG, Jacob S., General Manager, American Brass, Ltd., Eighth Street, New Toronto, Toronto 14, Ont., Canada.
- VIGNE, Albert, B.Sc., President, Bronze Alloys Company, 6264 St. Louis Avenue, St. Louis 20, Mo., U.S.A.
- WEGELIUS, Professor Edvard Albert, D.Sc., Director-General, Valtion Teknillinen Tutkimuslaitos Yljohtaja (State Institute for Technical Research), Lönnrotink 37, Helsinki, Finland.

### As Student Members

- BENTLEY, John Weston, B.Sc., Assistant, Experimental Department, British Aluminium Company, Ltd., Milton, Staffs.
- BHATTACHARYA, Sarnendu, B.Sc., Assistant Professor of Metallurgy, Birla Engineering College, Agra University, Pilani, Jaipur State, India.
- DUCKWORTH, Albert, B.Sc., Student, Honours School of Metallurgy, Manchester University.
- HOSKINS, John Albert, Student of Metallurgy, King's College, University of Durham, Newcastle-on-Tyne.
- KABI, Sanat Kumar, M.Sc., Department of Metallurgy, Indian Institute of Science, Bangalore 3, India.
- KEMPSON, Gerald Peter, B.A., Post-Graduate Student, St. John's College, Cambridge.
- KING, Robert Dick, B.Sc., A.R.T.C., Metallurgical Chemist, P.O. Box 700, Singapore.
- KISSLING, Rolf, Student of Metallurgy, Eidgenossische Technische Hochschule, Zürich, Switzerland.
- LOVETT, Peter Aubrey, Technical Assistant and Progress Organizer, H. Rollet and Company, Ltd., 6 Chesham Place, London, S.W. 1.
- MANOCHE, Rajindra, B.Sc., Student, Department of Metallurgy, Indian Institute of Science, Bangalore 3, India.
- NEWKIRK, John Burt, B.Met.E., M.S., Student of Metallurgy, Metals Research Laboratory, Carnegie Institute of Technology, Pittsburgh 13, Pa., U.S.A.

## NEWS AND ANNOUNCEMENTS

- PERRIOR, Bernard, Assistant in Metallurgical Research Laboratory, Fraser and Chalmers, Ltd., Erith, Kent.  
YOUNG, Li-Chow, B.Sc., M.Sc. (Eng.), Research Student, Department of Metallurgy, Birmingham University, Edgbaston, Birmingham.

The following 7 Ordinary Members and 4 Student Members were elected on 30 June 1948:

### As Ordinary Members

- DICKSON, K. B., Manager, Bureau of Technical Information, Research and Technology Department, Carnegie-Illinois Steel Corporation, Carnegie Building, Pittsburgh, Pa., U.S.A.  
JOBES, George Buchan, Foundry Manager (Non-Ferrous), English Electric Co., Ltd., Stafford.  
KOOISTRA, Lambert F., Mech.Eng., Research Engineer, Research and Development Department, Babcock and Wilcox Co., Alliance, O., U.S.A.  
LENZ, Carl K., Vice-President and Assistant Sales Manager, Kennecott Sales Corporation, 120 Broadway, New York 5, N.Y., U.S.A.  
MORTIMER, David Lawrence Fortescue, Development Engineer, The British Aluminium Co., Ltd., Salisbury House, London Wall, London, E.C.2.  
SMITH, Dana Wentworth, Ph.D., B.S., Chief Research Metallurgist, Fabricating Division, Permanente Metals Corporation, Spokane 6, Wash., U.S.A.  
ULRICH, Carl T., Vice-President and Treasurer, Kennecott Copper Corporation, 120 Broadway, New York 5, N.Y., U.S.A.

### As Student Members

- BROWN, David Charles, Student of Metallurgy, King's College, University of Durham, Newcastle-on-Tyne.  
LAYLAND, Robert Alan, Metallurgical Chemist, Bean's Industries, Ltd., Tipton, Staffs.  
ROSENQVIST, Dr. Terkel Nissen, Research Fellow, Institute for the Study of Metals, University of Chicago, Ill., U.S.A.  
SUDARSANAN, Andipat Pavithran, B.A., Student of Metallurgy, University of Leeds.

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## PERSONAL NOTES

MR. W. E. BALLARD, F.R.I.C., F.I.M., has been elected President of the Birmingham Metallurgical Society.

MR. BANI R. BANERJEE, B.Met., M.Eng., will visit India during the summer of this year, on leave from the Illinois Institute of Technology, Chicago, Ill., U.S.A., where he plans to resume his duties in the Department of Metallurgical Engineering in the autumn. While he is in India mail should be addressed to him at 23 Hindustan Rd., Calcutta.

MR. HORACE W. CLARKE, F.I.M., Managing Director of James Booth and Co., Ltd., and of John Wilkes, Sons, and Mapplebeck, Ltd., Birmingham, has been awarded the honorary degree of Doctor of Science of the University of Birmingham, in recognition

## NEWS AND ANNOUNCEMENTS

of his services to the University and to the non-ferrous metals industry.

DR. MAURICE COOK, who has been elected President of the Institution of Metallurgists, graduated at Manchester University in 1919 with First Class Honours in Metallurgy. He was Leblanc Medallist, and from 1919 to 1921 was Assistant Lecturer and Demonstrator in Metallurgy at Manchester University. Leaving Manchester, he went to King's College, Cambridge, where, from 1921 to 1924, he was engaged on research in the Goldsmiths' Laboratory. From 1924 to 1926 Dr. Cook was on the technical staff of Messrs. C. A. Parsons and Co., Ltd., Newcastle-on-Tyne. He joined the staff of Messrs. Kynoch, Ltd., in 1926, and is now a Director of the Metals Division, Imperial Chemical Industries, Ltd. Dr. Cook has been Chairman of the Midland Metallurgical Societies, President of the Birmingham Metallurgical Society, is a Member of Council of the Institute of Metals and of the British Non-Ferrous Metals Research Association, and is also a member of many technical Committees. His numerous original contributions to the literature of non-ferrous metallurgy are well known to members.

DR. W. CULLEN has been elected an Honorary Member of the Institution of Mining and Metallurgy, in recognition of his long and valued services to the mining and metallurgical profession and to the Institution.

DR. S. F. DOREY, C.B.E., F.R.S., has been elected a member of the General Council of the British Standards Institution, as a representative of the Engineering Division.

MR. F. BERTRAM ELLIOTT has, while serving in the Royal Air Force, obtained the degree of Bachelor of Metallurgy of the University of Sheffield.

MR. R. H. GARNER, B.Sc., A.M.I.E.E., A.M.I.Mech.E., has been appointed Principal of the County Technical College, Burnbank, Lanarkshire.

MR. ARTHUR GOUGE, B.Sc., Vice-Chairman of Messrs. Saunders-Roe, Ltd., received the honour of a knighthood in the Birthday Honours list.

DR. PAUL LACOMBE was appointed, last May, Professor of Metallurgy at the Ecole Supérieure des Mines de Paris, in succession to Professor Cornu-Thenard. He will still continue, however, in his former post as Maître de Recherches at the Centre National de la Recherche Scientifique in the laboratory at Vitry-sur-Seine directed by Professor Chaudron, and his address will remain unchanged.

MR. F. L. LAQUE, B.Sc., has been elected President of the National Association of Corrosion Engineers (U.S.A.).

PROFESSOR G. LETENDRE, Ph.D., B.A., Director of the Department of Mining and Metallurgical Engineering, Laval University, Quebec, Canada, has been awarded a Nuffield Foundation Traveling Fellowship in extraction metallurgy. He will arrive in England on 21 August and will be attending the Autumn Meeting of the Institute in Cambridge.



## NEWS AND ANNOUNCEMENTS

MR. W. G. MOCHRIE, London Manager of Tyseley Metal Works, Ltd., acted as delegate of the London Branch of the Institute of British Foundrymen to the recent convention of the American Foundrymen's Association in Philadelphia, and afterwards visited a number of works in the United States.

MR. G. T. MOTOCK, M.Sc., M.E., has been appointed Director of Research and Development to the Champion Rivet Co. of Cleveland, O., U.S.A.

MR. F. D. L. NOAKES, B.Sc., A.R.S.M., A.R.I.C., Lecturer in Metallurgy at the Royal School of Mines, London, has been awarded a Nuffield Travelling Scholarship and is now on a five months' tour of the Belgian Congo, Rhodesia, and the Union of South Africa, studying non-ferrous extraction metallurgy.

MISS D. L. PILE, A.I.M., has been elected Senior Vice-President of the Birmingham Metallurgical Society.

MR. A. PRINCE has been awarded the degree of B.Met. (First-Class Honours in Non-Ferrous Metallurgy) of Sheffield University.

MR. D. W. SMITH received the honour of M.B.E. in the Birthday Honours List.

MR. H. A. SNOW, A.I.M., until recently Metallurgist with the Aluminium Development Association, has taken up an appointment with the International Wire Co., Ltd., as Research and Development Engineer. His address is 48 Gloucester Place, London, W.1.

MR. E. E. SPILLETT was recently appointed Development Manager to the British Aluminium Company, Ltd.

DR. M. TCHORABJI SIMNAD has been awarded the Weston Research Fellowship of the American Electrochemical Society, and will be leaving England for the United States in the near future.

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## DEATH

The Editor regrets to announce the death on 31 May 1948 of MR. R. LLOYD GIBBINS, J.P., Joint Managing Director of the Birmingham Battery and Metal Company, Ltd. Mr. Lloyd Gibbins was a Member of Council of the British Non-Ferrous Metals Research Association, of which he was Chairman of the Finance Committee. He was a Member of Council of the Institute of Metals from 1924 to 1934, and was elected a Member of the Institute in 1917.

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## NEWS AND ANNOUNCEMENTS

### OTHER NEWS

#### INSTITUTION OF METALLURGISTS

The Annual General Meeting of the Institution was held at 4 Grosvenor Gardens, London, S.W.1, on 10 June 1948, when the Report of Council was presented and elections to the Council were announced. Vacancies on the Council were filled as follows : *President* : Maurice Cook, D.Sc., Ph.D. ; *Vice-Presidents* : E. W. Colbeck, M.A., and A. J. Murphy, M.Sc. ; *Honorary Treasurer* : C. J. Smithells, M.C., D.Sc. ; *Ordinary Members of Council Representing Fellows* : N. P. Allen, D.Sc., M.Met., and L. B. Pfeil, O.B.E., D.Sc., A.R.S.M. ; *Ordinary Member of Council Representing Associates* : L. Rotherham, M.Sc.

The newly-elected President of the Institution, Dr. Maurice Cook, was inducted into the Chair by the retiring President, Dr. J. W. Jenkin, and delivered his Presidential Address.

#### GESELLSCHAFT DEUTSCHER METALLHUTTEN- UND BERGLEUTE e.V.

The Gesellschaft Deutscher Metallhütten- und Bergleute e.V. was re-founded in 1947 under the name it used before 1938.

From 1938 to 1945 the Society was called the Gesellschaft Metall und Erz, and was responsible for the publication of *Metall und Erz*.

The Society has commenced publication of a new journal entitled *Zeitschrift für Erzbergbau und Metallhüttenwesen*, the successor to *Metall und Erz*. The first issue appeared in April 1948, and the Editor is Dr. W. Andrae, whose offices are at Erzstrasse 7, Clausthal-Zellerfeld (20b), Germany.

#### INTERNATIONAL FOUNDRY CONGRESS

The Congress will be held in Prague from 15 to 19 September 1948, and will be combined with a tour of visits to Czechoslovakian metallurgical works from 20 to 26 September. An International Foundry Exhibition will be held at the same time as the Congress.

Particulars may be obtained from Mr. L. K. Jeníček, Trída Jana Opletala 55, Prague II, Czechoslovakia.

### APPOINTMENTS VACANT

*To conform to the requirements of the Control of Engagements Order, 1947, these advertisements are published for the information only of those who are "excepted persons" under the Order.*

**ALUMINIUM DEVELOPMENT ASSOCIATION.** The Association wishes to appoint a man to be responsible for its general educational and publicity activities. These include distribution of technical information, particularly to schools and colleges; organization of exhibitions, film shows, and lectures; and rendering assistance to training establishments. The qualifications required are training in engineering or metallurgy, with some experience in educational work and preferably some knowledge of aluminium and its alloys. The commencing salary will be within the range of £650-£900 per annum, according to age, qualifications, and experience. Applications should be addressed to the Technical Director, The Aluminium Development Association, 33 Grosvenor Street, London, W.1.

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**ASSISTANT METALLURGIST** required for large engineering works in Lancashire. Candidates should possess a degree, or Assoc. Met., or A.I.M., and should have been employed in an industrial laboratory and had practical works experience and be interested in the application of research results to industrial practice. The position offers excellent opportunities to a man with personality and initiative. Age 28-35, commencing salary £550-£700 per annum, according to experience. Five-day week; staff superannuation fund. Reply to Box No. 238, Institute of Metals, 4 Grosvenor Gardens, London, S.W.1.

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# FURTHER EXPERIMENTS ON THE ADHESION 1134 OF TIN-BASE BEARING ALLOYS.\*

P. G. FORRESTER,† M.Sc., A.I.M., MEMBER, and L. T. GREENFIELD,†  
M.Sc., A.I.M., STUDENT MEMBER.

## SYNOPSIS.

The nature and properties of the bond between tin-rich alloys and various backing materials have been examined by microscopical and mechanical methods, particular attention being paid to the effects of intermetallic compounds at the bond. With mild steel, a layer of  $\text{FeSn}_2$  forms, but is not thick enough to embrittle the bond unless time and temperature of tinning are excessive. Embrittlement of the bond by  $\text{Cu}_6\text{Sn}_5$  deposited from the white metal can largely be avoided by centrifugal casting. Small amounts of residual nickel and chromium in the steel have no significant effect on bond strength. Bonds of moderate strength can be obtained on cast iron after treatment in fused salt baths.

The bond obtained with tin bronze, phosphor bronze, or gun-metal is of the same order of strength, under static loads, as is obtained with steel. The presence of  $\text{Cu}_6\text{Sn}_5$  at the bond results in some brittleness, as shown by chisel testing, but this can largely be avoided by reducing the temperature and time of tinning and lining. Good adhesion can also be obtained on aluminium after suitable preparation.

## I.—INTRODUCTION.

The adhesion of a bearing alloy to the backing material is an important factor in determining its behaviour in service. The strength of the bond depends on its physical continuity, which is determined largely by the lining and lining procedures employed; previous work has shown the importance of these factors and indicated the principles of good lining and tinning technique.<sup>1, 2, 4</sup>

The properties of the bond are also dependent on its metallurgical character, which is determined by the composition and properties of the backing material and the bearing alloy, and by the nature and extent of reaction between them. In a previous paper,<sup>5</sup> the authors have shown that the composition of the white metal has a considerable effect on its adhesion to mild steel. In particular, alloys of high copper content tend to form at the bond a layer of  $\text{Cu}_6\text{Sn}_5$  which has a marked embrittling effect.

The experiments described in the present paper had as their principal object the investigation of the influence of the basis material on the

\* Manuscript received 31 March 1948.

† Tin Research Institute, Greenford, Middlesex.

strength and metallurgical character of the bond. The basis materials studied were steels, cast irons, copper, bronzes, aluminium, and an aluminium alloy.

## II.—EXPERIMENTAL PROCEDURE.

In this, as in the previous work, specimens for adhesion testing have been prepared by methods similar to those used in lining bearings in practice. The only significant departure has been to use, for static-lining tests, flat plates in place of half-shells; this has been shown to have little effect on the strength or nature of the bond. In static-lining experiments the method used was essentially the same as that previously described.<sup>5</sup> The backing materials were obtained in the form of flat plates  $3 \times 2 \times \frac{1}{4}$  in., which were pre-tinned by a suitable method, which differed, of course, from one type of material to another. The tinned plates were reheated to  $280^{\circ}$  C. by re-dipping in the tin pot and clamped in a vertical lining jig, pre-heated to  $320^{\circ}$  C. The white metal was poured at a temperature  $50^{\circ}$  C. above its liquidus (unless otherwise stated), and the whole was then quenched from the bottom by water. The lining thickness was 0.25 in.

For centrifugal-lining experiments (which were confined to mild steel), cylinders of internal dia. 2 in., thickness  $\frac{1}{8}$  in., and length 2 in. were pre-tinned, immediately clamped in a suitable jig (pre-heated), and spun at various speeds. Sufficient white metal was poured in to give the correct lining thickness, and spinning was continued until the lining was completely solid.

The white metals used in the majority of the experiments were of nominal composition: antimony 7, copper  $3\frac{1}{2}\%$ , or antimony 7, copper 7% (referred to later as 7Sb/ $3\frac{1}{2}$ Cu and 7Sb/7Cu, respectively). Analyses showed close agreement with the nominal composition. For the investigation of the effect of steel composition a third alloy (antimony 7.68, copper 3.45%) was used.

The principal method of adhesion-testing used was that described by Chalmers,<sup>3</sup> in which an annular area of bond is isolated by drilling through the white metal with a trepanning drill and drilling a co-axial hole in the backing with a flat-ended drill. The plug of white metal is then forced off the backing in a compression rig. In this test there is a stress concentration at the inner edge of the annulus. On account of this stress concentration, a brittle bond may give a low value in the Chalmers test, even though its resistance to uniform static load is normal. To distinguish between a bond which is brittle and one which is weak (e.g. on account of discontinuities), it is necessary to supplement the



Chalmers test by a test in which a reasonably uniform load is applied. In some cases, therefore, a shear test was also used. The method, which has been described previously,<sup>5</sup> consists of taking a section of a lined plate about 2 in. long and  $\frac{1}{2}$  in. wide, isolating a short length of the bond with saw cuts through white metal and backing, and pulling this in a tensile-testing machine.

A slight tendency to brittleness is not always shown up by the Chalmers test. Accordingly a number of specimens were subjected to a tensile test, similar to that widely used in practice. The backing material was held in a vice and a chisel applied to the bond and hammered. The force required to separate the white metal from the backing, and the appearance of the fracture, give a rough indication of the toughness of the bond.

At least eight Chalmers tests were carried out for each set of conditions, and results were normally very consistent. In this paper, average results only are quoted, except in Table I, where detailed results are given to illustrate the degree of reproducibility obtained.

### III.—ADHESION TO STEEL.

#### 1. *General Considerations.*

Rhines<sup>6</sup> has shown that diffusion at an interface between two pure metals at constant temperature and pressure results in the formation of intermediate layers corresponding, in kind and order of occurrence, to the single-phase regions in the phase diagram at that temperature. The bond between tin and iron should, therefore, consist of  $\alpha$  (iron-base solid solution)—FeSn—FeSn<sub>2</sub>—tin. In practice, however, only FeSn<sub>2</sub> is visible in the bond of hot-dipped tinplate<sup>7</sup> and, in the authors' experience, the same holds for tin alloys bonded to steel. FeSn<sub>2</sub> is brittle and constitutes a potential source of weakness, but under normal tinning and lining conditions the FeSn<sub>2</sub> layer is thin and does not cause a brittle bond. Prolonged tinning at high temperature does embrittle the bond. (See Table I.)

#### 2. *The Influence of Steel Composition.*

The adhesion obtained by static lining was investigated for six different steels, with carbon contents ranging from 0.17 to 0.38%, nickel from 0.28%, and chromium up to 0.27%. This part of the research was carried out in co-operation with the Admiralty Engineering Laboratory, who supplied the steels and the white metal (antimony 7.68, copper 3.45%). Plates cut from these steels were degreased, pickled in 50% hydrochloric acid for 3 min., fluxed, tinned at 280° C., and

lined in the standard manner. The results of adhesion tests made by the Chalmers method are shown in Table II.

TABLE I.

Time of Tinning.	Temperature, ° C.	Bond Strength, tons/in. <sup>2</sup>	Average Bond Strength, tons/in. <sup>2</sup>
15 sec.	280°	5.31, 5.41, 5.02, 5.57, 5.44, 5.21, 5.25, 5.46.	5.3
15 sec.	380°	5.01, 4.68, 5.72, 5.35, 5.12, 5.08, 5.29, 5.31.	5.2
5 min.	280°	5.07, 5.28, 5.44, 5.50, 5.27, 5.21, 5.35, 5.25.	5.3
5 min.	380°	5.65, 4.88, 4.80, 5.60, 5.31, 5.17, 5.24, 5.20.	5.2
60 min.	380°	4.42, 5.05, 5.15, 4.61, 4.55, 5.15, 5.16, 4.62.	4.8
60 min.	450°	0.69, 0.70, 0.68, 0.55, 0.68, 0.74, 0.72, 0.66.	0.7

TABLE II.

Steel Composition, %.								Bond Strength, tons/in. <sup>2</sup> (average 24 tests).
C	Si	Mn	S	P	Ni	Cr	Mo	
0.17	0.18	0.57	0.027	0.034	Nil	0.02	0.01	5.6
0.19	0.23	0.55	0.027	0.033	0.26	0.26	0.01	5.5
0.29	0.33	0.60	0.026	0.035	Nil	0.01	Nil	5.5
0.29	0.19	0.40	0.028	0.035	0.27	0.26	Nil	5.7
0.39	0.29	0.70	0.026	0.034	Nil	0.02	0.01	5.4
0.38	0.26	0.71	0.026	0.032	0.28	0.27	0.01	5.5

There is no significant difference between these adhesion values, and it appears safe to conclude that nickel and chromium, in amounts likely to be present as residual elements, have no significant effect on adhesion. This conclusion is in conformity with the results obtained by Prytherch,<sup>21</sup> who found similar adhesion figures for mild steel, medium-carbon steel, silver steel, and nickel steel, though in the latter case a modified pickling technique was required for maximum adhesion.

### 3. *The Effect of Centrifugal Casting.*

Centrifugal casting of tin-base bearing alloys causes segregation of the intermetallic compounds  $\text{Cu}_6\text{Sn}_5$  and  $\text{SbSn}$ . The  $\text{Cu}_6\text{Sn}_5$ , which is denser than the liquid matrix, segregates towards the bond, while the  $\text{SbSn}$ , which is slightly less dense, segregates towards the inner surfaces. This effect is illustrated in Fig. 1 (Plate XLII) which shows a photomicrograph of  $12\text{Sb}/3\frac{1}{2}\text{Cu}$  cast centrifugally into a pre-tinned steel shell at a

speed of rotation equivalent to 1000 ft./min. If, as is customary in practice, the inner layers are machined off, the metal left is considerably richer in copper and slightly poorer in antimony than the original alloy. The depth of the copper-rich layer depends on the initial copper content; this may be seen by comparing Fig. 1 and Fig. 2 (Plate XLII), which show respectively 12Sb/3½Cu and 7Sb/7Cu cast under similar conditions. There are, therefore, two ways of obtaining a lining of composition, say, antimony 7, copper 7%. One is to cast by ordinary static methods an alloy of this initial composition. The second is to cast centrifugally an alloy of initial composition about antimony 8, copper 3½%. It has been shown <sup>5</sup> that the first method tends to give a brittle bond, resulting from the precipitation of Cu<sub>6</sub>Sn<sub>5</sub>. The present experiments were carried out to determine whether the second method (centrifugal lining) also gave a brittle bond.

Two alloys 7Sb/3½Cu and 7Sb/7Cu were cast centrifugally on to the re-tinned mild-steel cylinders at various speeds of rotation. Adhesion tests by the Chalmers method and also chisel tests were made on the lined shells. In addition analyses were carried out on turnings obtained (a) from a 0.02 in. layer at the inside and (b) from a 0.02 in. layer at the bond. The results are shown in Table III.

TABLE III.

Alloy.	Speed of Rotation, ft./min.	Average Bond Strength, tons/in. <sup>2</sup>	Analysis, %.			
			Near Bond.		Free Face.	
			Cu	Sb	Cu	Sb
7Sb/3½Cu	735	4.8	6.7	6.5	1.8	7.2
"	1000	4.7	6.9	6.1	1.8	7.3
"	1250	4.6	8.3	6.2	1.8	7.5
"	1875	4.6	10.9	5.8	1.4	7.5
"	Static lining (standard conditions)	5.4	...	...	...	...
7Sb/7Cu	1000	4.9	...	...	...	...
"	Static lining (standard conditions)	2.6	...	...	...	...

For comparison purposes the bond strength of the same two alloys statically lined <sup>5</sup> are included in the Table. It will be seen that by centrifugal casting a lining of copper content 7-11% can be obtained with bond strength of 4.6-4.8 tons/in.<sup>2</sup> This compares very favourably with that of a lining of copper content 7% obtained by static casting.



Chisel tests showed tough bonds with all the centrifugal linings, though the bond of 7Sb/7Cu statically lined was very brittle.

Fig. 3 (Plate XLII) shows a photomicrograph of the bond obtained with 7Sb/3½Cu, lined at 1250 ft./min. There is a high concentration of Cu<sub>6</sub>Sn<sub>5</sub> near the bond, but no evidence of the formation of a layer at the bond, as occurs in static lining. It is possible that the stirring action obtained in centrifugal casting causes Cu<sub>6</sub>Sn<sub>5</sub> crystals to form at random instead of on the nuclei present at the bond.

Centrifugal casting thus affords a means of obtaining a lining of high copper content with a satisfactory bond strength. This is of considerable practical significance, for in general the fatigue strength of tin-base alloys increases with increase of copper content.<sup>8</sup>

#### IV.—ADHESION TO CAST IRON.

With cast iron the use of ordinary pickling methods leads to very unsatisfactory tinning and very poor adhesion, owing to the formation of graphite sludge on the surface. Better adhesion can be obtained by electrodepositing a layer of pure iron on the cast-iron surface preparatory to tinning.

A much more satisfactory preparation for cast iron is to immerse in fused salts before tinning. Cresswell<sup>9</sup> has described in detail two suitable fused-salt processes, one using zinc chloride–sodium chloride eutectic, the other using the sodium nitrate–potassium nitrate eutectic. Cresswell has also given the results of some adhesion tests on cast iron tinned by this method and lined with white metal. The authors, in collaboration with Mr. Cresswell, carried out further tests to examine the influence of cast-iron composition and other factors on the bond strength.

Both chloride and nitrate processes were investigated. The chloride process consists of mechanical cleaning, pre-heating to 300° C., immersing in the chloride bath at 300°–350° C., and normal hot tinning. This process exposes a clean iron surface, except where a graphite flake extends to the surface and causes a discontinuity. The nitrate process is more complicated but does actually remove the graphite by oxidation. The steps are as follows :

- (1) Mechanically clean and degrease.
- (2) Pickle in 10% sulphuric acid at 85° C.
- (3) Immerse in nitrate bath at 350°–400° C.
- (4) Pickle in 10% hydrofluoric acid to remove oxide film.
- (5) Flux and immerse in tin.

Plates tinned by one or other of these processes were lined in the standard manner with 7Sb/3½Cu. For comparison purposes other

specimens were tinned after electroplating with pure iron and lined in the same manner. Results of adhesion tests are given in Table IV.

The Chalmers-test figures obtained after the nitrate-bath treatment are of the order of half those obtained on steel, while the chloride bath gives lower figures. The shear test on grey cast iron also gave a value about half that obtained on steel. This test is, as noted earlier, not

TABLE IV.

Composition, %.				Type of Adhesion Test.	Average Bond Strength, tons/in. <sup>2</sup>		
Total C	S	P	Mn		Nitrate Bath Treatment.	Chloride Bath Treatment.	Electro-deposition with Iron.
3.0	1.45	0.12	0.9	Chalmers test	2.5	1.8	1.3
3.10	1.90	0.16	0.7	"	2.8	1.9	1.3
3.30	2.20	0.2	0.8	"	2.4	1.3	1.3
3.25	3.00	1.0	0.55	"	3.5	1.2	0.9
Grey iron, unknown composition				"	3.5	2.9	...
"	"	"	"	Shear test	1.8	1.7	...

sensitive to the type of weakness (brittleness) caused by intermetallic compounds, so it is probable that the weakness lies in actual discontinuities. Such discontinuities may be inevitable with a material so heterogeneous as cast iron. On chisel testing, the bond was always fractured by a moderate blow. This apparent brittleness, previously reported by Holligan,<sup>10</sup> is probably due to the notch effect of discontinuities.

In considering the results it should be borne in mind that lining after normal pickling methods results in practically no adhesion. The salt-bath treatments, especially the nitrate bath, give a bond which is weaker than is obtained with steel, but which is, in most cases, adequate for the thick linings usually employed with cast iron. The composition of the cast iron, within the range examined, appears to have little influence on adhesion.

## V.—ADHESION TO BRONZE.

### 1. General Considerations.

At normal tinning and lining temperatures two intermediate phases exist between copper and tin.<sup>11</sup>  $\zeta$ , based on  $\text{Cu}_6\text{Sn}_5$ , and  $\epsilon$ , based on  $\text{Cu}_3\text{Sn}$ . Both phases are hard and brittle and are potential sources of brittleness. Metallographic examination of tin-copper bonds shows that the  $\zeta$  phase predominates, though occasional traces of the  $\epsilon$  phase may be found.

2. *Experimental Procedure and Results.*

Ingots of bronze of various compositions were prepared by the methods described by Pell-Walpole.<sup>12</sup> Plates for lining and adhesion testing were prepared from these ingots. In addition, parts of two of the ingots were cold rolled to about 30% of their original thickness, with several intermediate anneals (necessitated by the low power of the rolls used). They were not annealed after the last rolling, so plates prepared from these rolled ingots were in the cold-worked state. All the plates were degreased, pickled in cold 25% nitric acid for 1 min., fluxed, tinned at 280° C. (except where otherwise stated), and lined under standard conditions with 7Sb/3½Cu. Results of adhesion tests are shown in Table V.

TABLE V.

Composition (copper remainder).	Condition.	Diamond Pyramid Hardness No.	Average Bond Strength, tons/in. <sup>2</sup>
10% tin	As cast	110	5.0
" " "	Cold rolled	150	5.1
14% tin	As cast	140	5.3
" " "	Cold rolled	180	4.5
14% tin, 1% phosphorus	As cast	170	5.2
10% tin, 2% zinc	As cast	112	5.2

These results show that satisfactory adhesion, as measured by the Chalmers test, is obtainable on all these alloys. Cold working causes a slight reduction in the bond strength of the 14%-tin alloy. Chisel tests, however, showed that the bond obtained was in every case somewhat brittle, a moderate blow completely detaching the lining from the plate. This brittleness is almost certainly due to the layer of  $\text{Cu}_6\text{Sn}_5$  formed by reaction between the tin and the bronze. This layer, shown in Fig. 4 (Plate XLIII), is very much thicker than the corresponding layer of  $\text{FeSn}_2$  obtained with steel under similar tinning and lining conditions. The adhesion will, of course, be further impaired if additional  $\text{Cu}_6\text{Sn}_5$  is deposited on the bond from the white metal, as may occur with alloys of high copper content.

Experiments were made to determine whether the bond brittleness could be reduced by modification of the tinning and lining conditions. In the first place, cleaned and fluxed copper plates were fixed in the lining jig and the whole placed in a tin bath at a controlled temperature. This bath served merely to heat the jig and plate, access of tin to the inside being prevented. Tin-copper eutectic alloy (0.75% copper) heated to the same temperature was then poured into the jig. After a





FIG. 1.—Steel Centrifugally Lined with 12Sb/3½Cu. Etched.  $\times 15$ .

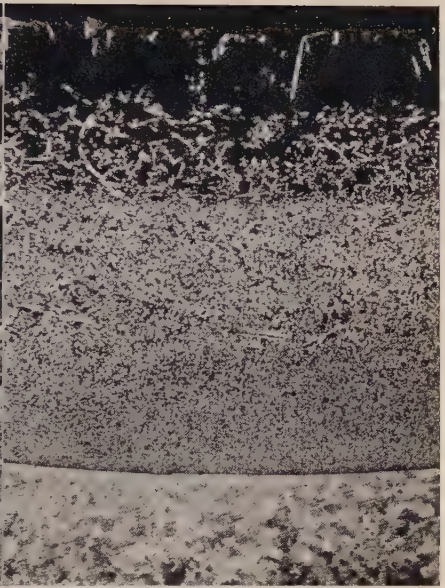


FIG. 2.—Steel Centrifugally Lined with 7Sb/7Cu. Etched.  $\times 15$ .

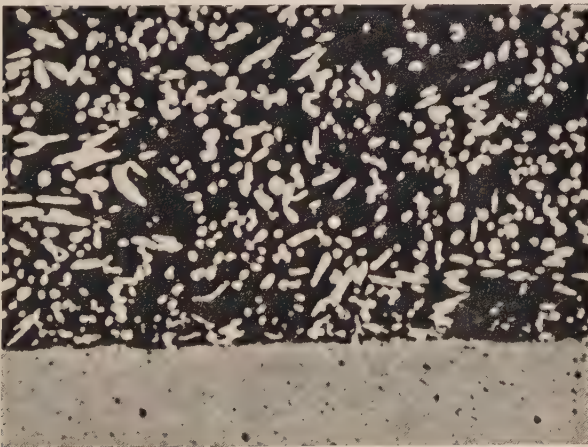


FIG. 3.—Steel Centrifugally Lined with 7Sb/3½Cu. Etched.  $\times 200$ .

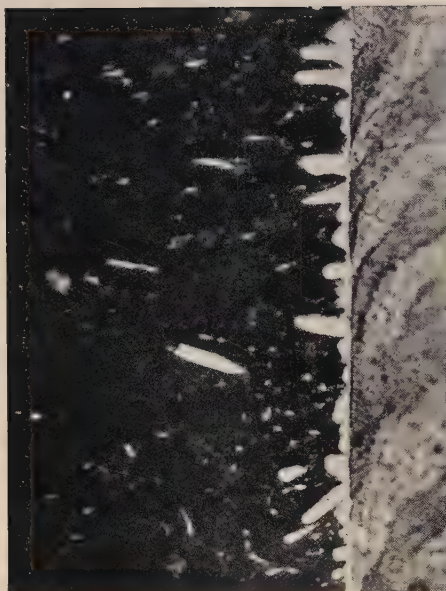


FIG. 4.—Bronze Tinned at 280° C., Statically Lined with 7Sb/3½Cu at 380° C. Bronze heat-tinted, white metal etched. × 500.



FIG. 5.—Bronze Tinned at 250° C., Statically Lined with 7Sb/3½Cu at 330° C. Bronze heat-tinted, white metal etched. × 500.

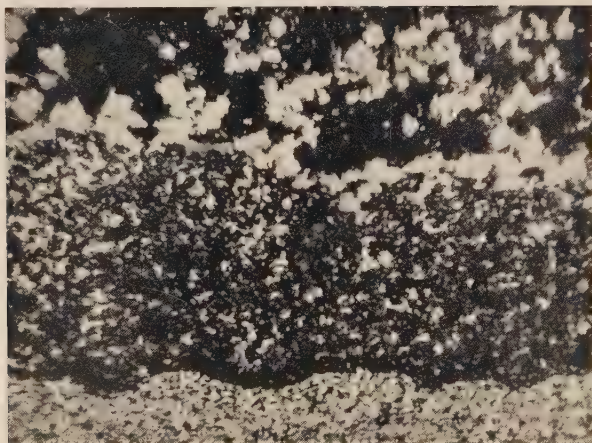


FIG. 6.—Aluminium Statically Lined with 7Sb/7Cu. Etched. × 500.

controlled time the jig was quenched in water and the lined plate sectioned for metallographic examination and chisel tests. Results are given in Table VI.

TABLE VI.

Temperature, ° C.	Time.	Appearance of Bond.	Chisel-Test Result.
250°	15 sec.	Practically no $\text{Cu}_6\text{Sn}_5$	Tough bond.
250°	5 min.	Trace of $\text{Cu}_6\text{Sn}_5$	" "
450°	15 sec.	Thin layer of $\text{Cu}_6\text{Sn}_5$	Rather brittle bond.
450°	5 min.	Thick layer of $\text{Cu}_6\text{Sn}_5$	Very brittle bond.

These results showed that the thickness of the  $\text{Cu}_6\text{Sn}_5$  layer could be greatly reduced if the temperature and time of the reaction were reduced to a minimum. A similar experiment was carried out with 10%-tin bronze lined with tin-copper eutectic at 250° C. for 15 sec. Rather more  $\text{Cu}_6\text{Sn}_5$  was obtained than with pure copper, but the chisel-test result was still good. On the basis of these experiments a 10%-tin bronze plate was tinned and lined with 7Sb/3½Cu alloy in the normal way except that times and temperatures were reduced to the minimum reasonably possible. Tinning was at 250° C. for 15 sec.; the metal was poured from 300° C. (just above its liquidus temperature) and immediately quenched. The bond obtained was found on chisel testing to be as tough as that normally found with steel. It was, in fact, impossible to fracture the bond, the chisel cutting through the white-metal. Fig. 5 (Plate XLIII) is a photomicrograph of this bond.

It thus appears that with small shells of bronze an excellent bond can be obtained by keeping times and temperatures of tinning and lining to the minimum; it is recognized that difficulties are likely to arise with large shells, which cannot conveniently be tinned as rapidly as smaller ones and which must necessarily be cooled more slowly.

# VI.—ADHESION TO ALUMINIUM.

If the surface of an aluminium specimen is completely freed from its oxide skin, it is wetted quite readily by molten tin. Tin and aluminium, however, have very little mutual solid solubility<sup>13</sup> and form no compounds, so that the bond between tin and aluminium consists of an interface between substantially pure metals which have a very dissimilar crystal structure. The strength of the bond obtainable between aluminium and tin alloys is therefore open to question on theoretical grounds. Accordingly, experiments were made to determine the bond strength obtainable in practice.



1. *Methods of Tinning.*

Wet pickling methods are unsuitable as a preparation for aluminium before tinning, for even if the oxide film is removed it re-forms before the surface can be brought into contact with molten tin. In the present work three methods of tinning were tried, and are described below.

(a) *Scratch-Brushing While Immersed in Molten Tin.*

The specimen was held under the surface of molten tin maintained at 280° C. and scrubbed vigorously with a wire brush. No flux was used on the tin pot, and the aluminium was not prepared in any way. After 2 or 3 min. scrubbing, a continuous coating of tin was obtained.

(b) *Use of Fluxes.*

In preliminary work, the most promising results were obtained with chloride fluxes, and further experiments were confined to two fluxes of this type. The first of these was a ternary eutectic, namely zinc chloride 75, sodium chloride 11, potassium chloride 14%. The procedure adopted was to immerse the aluminium specimen in the salt bath for about 4 min. and then to transfer it to the tin pot. Various salt-bath and tin-pot temperatures were tried. It was found that satisfactory tinning was only obtained when the tin pot was maintained above 350° C. At lower temperatures a solid crust formed on the aluminium surface, probably because of contamination of the flux layer with aluminium, resulting in an increase in melting point. The flux-bath temperature was found to be less important, 280°–300° C. giving satisfactory results.

The relatively high tinning temperature of 350° C. would limit the practical application of this salt-bath process on account of its effect on the properties of many aluminium alloys. Experiments were, therefore, carried out with a flux of lower melting point, namely zinc chloride 68, sodium chloride 10, potassium chloride 12½, ammonium chloride 9½%. Using this flux, it was found that tinning could be obtained with both flux bath and tin pot at 280° C. Tinning at this temperature was rather slow, but could be accelerated by occasional application of powdered ammonium chloride to the surface of the specimen.

(c) *Replacement Tinning Followed by Hot Dipping.*

By dipping aluminium in hot caustic soda, then in cold nitric acid and finally in sodium stannate solution, a grey deposit of tin can be obtained on the surface. Experiments were carried out in which this process was used as a preparation for hot dipping, but in no case was satisfactory tinning obtained.

## 2. Bond Strengths on Aluminium.

Using tinning methods (a) and (b), specimens of aluminium were tinned with 7Sb/3½Cu and 7Sb/7Cu. A few plates of a commercial aluminium alloy were also lined after tinning by the flux-bath method. Results of adhesion tests are given in Table VII.

TABLE VII.

Base Material.	Tinning Method.	Bearing Alloy.	Average Bond Strength, tons/in. <sup>2</sup>
Aluminium (commercial purity)	Wire-brush scrubbing	7Sb/3½Cu	4.6 (Chalmers test). 2.3 (Shear test).
"	"	7Sb/7Cu	4.8 (Chalmers test). 2.1 (Shear test).
"	"	7Sb/3½Cu	4.1 (Chalmers test).
Aluminium alloy	Salt-bath (quaternary)	7Sb/3½Cu	4.2 "

It will be noted that the adhesion of 7Sb/3½Cu is rather lower than is obtained on steel; on the other hand, 7Sb/7Cu gives better adhesion (as measured by the Chalmers test) than is obtained on steel. Fig. 6 (Plate III) shows a photomicrograph of the bond obtained with this alloy, which differs in several respects from that between the same alloy and steel. It will be seen that there is no tendency for Cu<sub>6</sub>Sn<sub>5</sub> to form on the aluminium; evidently the aluminium does not, like steel, provide nuclei for the crystallization of this compound. Adjacent to the bond, there is a band in which the structure of the white metal is abnormal, the Cu<sub>6</sub>Sn<sub>5</sub> being much more finely distributed than is usually the case. Aluminium is known to modify the structure of white metal, and this abnormal structure is doubtless due to this effect. The aluminium must have diffused into the white metal while the latter was still molten, for diffusion in the solid state could not have influenced the crystallization of the Cu<sub>6</sub>Sn<sub>5</sub>. Beyond the abnormal zone there is a rugged layer of relatively coarse Cu<sub>6</sub>Sn<sub>5</sub>. The cause of this Cu<sub>6</sub>Sn<sub>5</sub> layer is uncertain, but it is possible that the aluminium in the layer near the bond suppressed the formation of Cu<sub>6</sub>Sn<sub>5</sub>, causing the liquid to become supersaturated in respect to copper. This excess copper would then tend to precipitate in an aluminium-free zone, causing the abnormal form of segregation. All the bonds obtained on aluminium were found to be fairly tough when subjected to the chisel test, so it appears that the Cu<sub>6</sub>Sn<sub>5</sub> layer which forms away from the bond has no adverse effect. These experiments show that a satisfactory bond can be obtained

between tin-base white-metal and aluminium and offer no support to the hypothesis that solid-solution or compound formation is essential for good adhesion.

#### VII.—CONCLUSIONS.

(1) Adhesion to mild steel tinned by suitable methods is unaffected by small amounts of residual nickel and chromium, or by carbon content up to 0.4%.

(2) Embrittlement of the bond by deposition of  $\text{Cu}_6\text{Sn}_5$  from the white metal can be largely overcome by centrifugal casting.

(3) Adhesion to cast iron after salt-bath treatment is moderately good.

(4) Tin bronzes with or without phosphorus and zinc, give a bond of strength, as measured by static testing, of the same order as steel. There is, however, some tendency to brittleness, owing to the  $\text{Cu}_6\text{Sn}_5$  formed in the bond. The thickness of this layer and the consequent brittleness can be reduced by keeping times and temperatures of tinning and lining to a minimum.

(5) The bond between suitably prepared aluminium and tin-base Babbitt is almost as strong as that obtained on steel or bronze and shows no tendency to brittleness.

#### ACKNOWLEDGEMENTS.

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13. (Awaiting publication.)



# THE RELATIONSHIP BETWEEN STRESS AND STRAIN FOR HOMOGENEOUS DEFORMATION.\* 1135

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## SYNOPSIS.

A simple relationship with a rational basis has been found to connect stress with strain for a series of homogeneous compression curves published by Cook and Larke. At large deformations each of the curves becomes asymptotic to a definite stress, and the difference between this final stress and the threshold stress at which plastic deformation begins to become appreciable may therefore be regarded as the total stress capacity of the material. Similarly, the difference between any particular applied stress and that which is finally attained is the stress capacity remaining available after the application of the stress in question. Defining the plastic modulus, comparable with the elastic modulus, as the rate of change of stress with respect to true (logarithmic) strain, it is shown that *the plastic modulus at any instant is proportional to the available stress capacity.*

The same relationship appears to hold for tension as well as for compression as long as the deformation remains homogeneous. For example, it seems to be true up to the incidence of necking in the tensile test, and even beyond it in special circumstances which are described.

While this relationship cannot be regarded as established, it is tentatively put forward and discussed with illustrative examples in the hope of stimulating further research.

## I.—INTRODUCTION.

At the outset it must be made clear that the conceptions to be described are speculative in character and are based on experimental evidence which is admittedly meagre. They are put forward without dogmatism in the hope that interest may be stimulated and investigations provoked. During recent years, consciousness of the inadequacy of normal tensile and compression tests to give fundamental information concerning the behaviour of materials under stresses above the elastic range has been evident in numerous publications. Most writers agree in advocating the use of true stress, or stress calculated on the sectional area supporting the load, but beyond this there is much diversity of opinion. Several different definitions of strain are in use, and each worker claims that one or another of them leads to a simple relationship between stress and strain at least part of the deformation curve. Osgood<sup>1</sup> has recently summarized and discussed no less than 22 empirical equations proposed

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by different investigators since Hooke's law was propounded in 1678 and this is by no means an exhaustive list. The confusion is largely due to the fact that no satisfactory data have been available for analysis, because the non-axial stresses associated with necking make interpretation of the tensile test speculative, while ordinary compression tests are complicated by the effects of friction between the ends of the specimen and the compression blocks. To review the present chaotic situation in detail seems unnecessary, because Cook and Larke<sup>2</sup> have provided a new starting point by devising a means of determining the basic stress-strain curve for homogeneous compression free from friction.

Cook and Larke give the basic compression curves for 8 different materials, and it has been found that the same relationship between stress and deformation exists for all of them, differing only in the constant characteristic of the individual alloys. The equation representing this relationship, while admittedly empirical, has a more rational significance than most of those advanced previously. It appears, moreover, to be applicable to tensile tests up to the commencement of necking, and probably beyond if precautions are taken to ensure that the stress-strain curve is obtained under conditions of homogeneous deformation. Even without such expedients, however, the curve beyond the necking point can be generated mathematically from data readily obtainable with ordinary testing equipment.

It is fully realized that any equation purporting to connect stress with deformation over a wide range for a polycrystalline material is, at best, merely a statistical average of effects on individual crystals, the behaviour of which alters as deformation proceeds. Such matters, as well as the influence of temperature and strain rate, are beyond the scope of the present paper.

## II.—SYMBOLS AND DEFINITIONS.

The word "homogeneous" is used to describe deformation in which all parts of the specimen are deformed to the same extent and in the same manner.

All stresses considered in this paper are true stresses unless the contrary is stated. Loads divided by the original sectional area are referred to as "nominal stresses", the ordinary tensile strength being a typical case. All numerical stresses are in tons per square inch.

\* Precision tensile data have recently been published by Low and Garofalo in support of the Hollomon-Gensamer equation, namely  $S = Ke^n$ , where  $S$  is the true stress and  $e$  the logarithmic strain, while  $K$  and  $n$  are constants. The equation does not fit the homogeneous compression curves of Cook and Larke.

The following symbols and definitions are used :

$A_0$  = sectional area before deformation.

$A$  = sectional area after deformation.

$L_0$  = length before deformation.

$L$  = length after deformation.

Because the volume remains sensibly constant :

$$A_0 L_0 = AL \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$W$  = applied load.

$S$  = true stress =  $W/A$ .

$N$  = nominal stress =  $W/A_0$ .

$R$  = strain ratio : the ratio between the final and original sectional area or length, so arranged that the *greater* area or length, whether before or after deformation, appears in the numerator of the fraction. Thus the strain ratio  $R$  is always greater than unity, and the logarithmic strain is kept positive.

For tension :

$$R = L/L_0 = A_0/A = S/N \quad . \quad . \quad . \quad . \quad (2)$$

For compression :

$$R = L_0/L = A/A_0 = N/S \quad . \quad . \quad . \quad . \quad (3)$$

$e$  = Ludwig's true, or logarithmic strain

$$= \int_{L_0}^L dL/L = \ln \frac{L}{L_0} = \ln R,$$

and similarly for area ratios and for compression.

$P$  = the instantaneous plastic modulus, comparable with Young's modulus, and defined as the instantaneous rate of change of true stress with respect to true strain, i.e.  $P = dS/de$ . The reciprocal of this differential coefficient, namely  $1/P = de/dS$ , is a measure of the readiness with which the material may be deformed, or more simply of its *deformability*.

$S_0$  = the initial or threshold stress at which homogeneous plastic deformation begins to be appreciable. It is usually above the limit of proportionality, and corresponds roughly with the 0.1% proof stress.

$S_\infty$  = the final constant stress, attainment of which at indefinitely large strains appears to be a characteristic of homogeneous deformation.





that of the tangent, is numerically equal to the ordinary tensile strength. In such a curve the conditions at the maximum load are therefore :

$$\text{Ordinate} = S_m, \quad \text{Abscissa} = R_m, \quad \text{Slope} = N_m \quad . \quad . \quad (6)$$

Similarly, when using logarithmic strain, it can be shown that the slope of the curve at the maximum load is numerically equal to the true stress at this point, so that :

$$\text{Ordinate} = S_m, \quad \text{Abscissa} = e_m, \quad \text{Slope} = S_m \quad . \quad . \quad (7)$$

It should be emphasized that equations (6) and (7) are universally true and make no assumptions with regard to the form of the stress-strain curve. Their derivation is outlined in the Appendix.

#### IV.—HOMOGENEOUS COMPRESSION CURVES.

Cook and Larke<sup>2</sup> determined the stress-strain relationship under homogeneous compression for the 8 copper-base alloys shown in Table I. Their results are reproduced in Fig. 1, and though the curves only extend

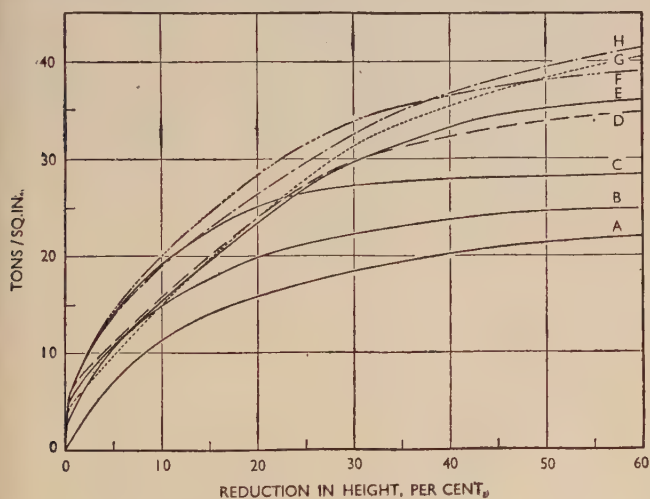


FIG. 1.—Homogeneous Compression Tests for Copper Alloys. (Cook and Larke.) (For key see Table I.)

to 60% reduction in height, it appears that each is already approaching a constant stress under which the load necessary to promote deformation is directly proportional to the increasing sectional area. This is particularly apparent in the case of curve C for cupro-nickel, but the free-hand





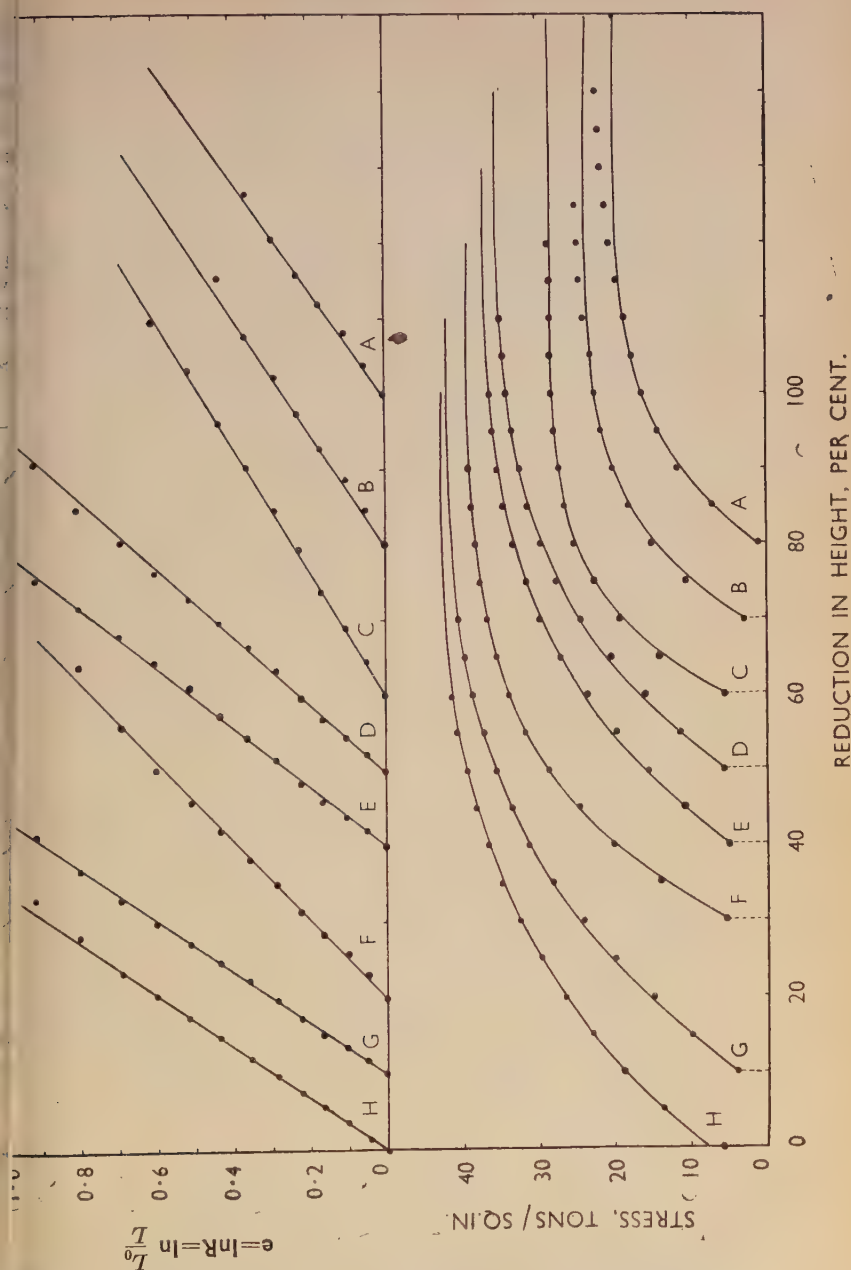


FIG. 2.—Analysis of the Homogeneous Compression Tests of Cook and Larke.  
 N.B.—The individual curves have been displaced along the horizontal axis for clarity. All should spring from the origin.

The constants  $S_{\infty}$ ,  $S_0$ , and  $k$  of this equation are given for the individual materials in Table II, and it must be emphasized that the parameters so found are peculiar to the conditions of temperature, strain rate, grain-size, &c., used by Cook and Larke in their experiments. The most noticeable feature of the Table is that the presence of nickel in the alloys tends to diminish the value of  $k$ ; this is reflected in the curves for cupro-nickel and nickel silver.

In the lower part of Fig. 2 the curves are re-plotted on co-ordinates similar to those originally adopted by Cook and Larke, namely true stress and percentage reduction in height. The curves have not, however, been drawn through the experimental points but are mathematically identical with the straight lines which appear above them, using the constant given in Table II. Agreement between the curves and experimental data

TABLE II.—*Constants Derived from the Homogeneous Compression Curves of Cook and Larke.*

Curve.	Material.	Threshold Stress $S_0$ , tons/in. <sup>2</sup>	Final Stress $S_{\infty}$ , tons/in. <sup>2</sup>	$k$ .
<i>A</i>	Copper	1.0	19.7	0.14
<i>B</i>	Gilding Metal	2.8	23.5	0.13
<i>C</i>	Cupro-Nickel	5.5	28.3	0.12
<i>D</i>	70 : 30 Brass	5.5	35.3	0.22
<i>E</i>	64 : 36 Brass	5.0	37.0	0.25
<i>F</i>	Nickel Silver	5.5	39.0	0.19
<i>G</i>	Aluminium Bronze	4.0	42.0	0.29
<i>H</i>	Phosphor Bronze	8.0	42.5	0.29

is good, except that the threshold stress demanded by the general trend of curve *H* for phosphor bronze is somewhat higher than the experimental value, and that curves *A* for copper and *B* for gilding metal lie beneath the experimental points for large deformations. Even for these, however, the fit is satisfactory up to strains well beyond those at which necking would occur in tension, i.e. well into the region in which internal friction under ordinary, as distinct from homogeneous, compression becomes appreciable. It is possible that the method of testing devised by Cook and Larke did not entirely succeed in correcting for the effect of internal friction in the case of these two soft materials.

Differentiation of equation (9) gives :

$$\frac{de}{dS} = \frac{k}{S_{\infty} - S} = \frac{k}{C} \quad . \quad . \quad . \quad . \quad (11)$$

Now the differential coefficient  $de/dS$  represents the amount of deformation caused by a given small increment in stress, and can therefore

arded as a measure of the *deformability* of the material at the instant under consideration. Thus equation (11) signifies that for homogeneous compression *the deformability at any instant is inversely proportional to available stress capacity*. Alternatively the reciprocal function :

$$\frac{dS}{d\epsilon} = \frac{C}{k} = P \quad . \quad . \quad . \quad . \quad . \quad (12)$$

implies that *the instantaneous plastic modulus is proportional to the available stress capacity*. Though empirical in its derivation, the relationship seems, therefore, to have a more rational significance than most which have been proposed previously.

#### V.—APPLICATION TO TENSION.

Up to the maximum load, deformation under tension apparently remains homogeneous, but with the incidence of necking a complex stress system is introduced. Stress-strain curves based on the minimum cross-sectional area at the centre of the neck show no sign of reaching a constant stress at large deformations, as is the case under homogeneous compression. This is not surprising in view of the secondary radial stresses which are known to exist in the neck, but it increases the difficulty of ascertaining whether the form of equation which appears to satisfy homogeneous compression is equally applicable to homogeneous tension. The following solution of the problem is based on the fact, already mentioned and discussed more fully in the Appendix, that the plastic modulus at the maximum load is numerically equal to the corresponding true stress.

For conditions at the maximum load, combination of equation (12) with equation (7) shows that :

$$P_m = S_m = \frac{S_\infty - S_m}{k}$$

hence :

$$S_\infty = (1 + k) S_m \quad . \quad . \quad . \quad . \quad . \quad (13)$$

Substitution of this value of  $S_\infty$  in equation (10) and collection of like terms gives :

$$R_m = \left\{ \frac{1}{k} \left( 1 + k - \frac{S_0}{S_m} \right) \right\}^k \quad . \quad . \quad . \quad . \quad (14)$$

Since the values of the threshold stress  $S_0$  and of the true stress  $S_m$  and strain ratio  $R_m$  at the maximum load can readily be ascertained by direct experiment without involving the ambiguities attendant upon necking, equations (13) and (14) together provide sufficient information for the



determination of both  $S_\infty$  and  $k$ , and the curve so found can be compared with the experimental stress-strain curve up to the necking point. Moreover, it can be extrapolated to greater deformations if required.

Though the algebraic solution of equation (14) for  $k$  is difficult, it is a simple matter to compute and plot a nest of curves of  $R_m$  against the ratio  $S_0/S_m$  for a series of fixed values of  $k$ . Such curves, covering a restricted but useful range, are shown in Fig. 3, which carries a small scale insert to indicate more broadly the general form of the function. From experimental determinations of  $R_m$  and  $S_0/S_m$ , the corresponding value of  $k$  can be read from this diagram. It is noteworthy that the function is less sensitive to  $S_0/S_m$  than it is to  $R_m$ , and thus ambiguities in the determination of the threshold stress  $S_0$  are relatively unimportant. This is fortunate in view of the lack of a precise definition of the threshold stress.

The results obtained by the use of Fig. 3, and the procedure involved, can best be illustrated by means of examples.

A tensile specimen of annealed electrolytic copper rod was tested with micrometer measurements of diameter at a series of loads up to the maximum. Sectional areas were obtained from the diameter measurements, and true stresses calculated. The ratio of the original sectional area to that under load was accepted as the strain ratio corresponding to each true stress so determined, and the data are plotted as black circles in Fig. 4. It will be noted that the first two points lie below the general trend of the curve, which if extrapolated smoothly cuts the axis of zero strain ratio (zero deformation) at a stress of approximately 3.0 tons/in.<sup>2</sup>. This should be accepted as the threshold stress, discounting the fluctuations with which the curve links up with the elastic line. The true stress at the maximum load was found to be 19.7 tons/in.<sup>2</sup>, and the corresponding strain ratio was 1.40<sub>5</sub>. The co-ordinates  $S_0/S_m = 3.0/19.7 = 0.152$  and  $R_m = 1.40_5$  define a point on Fig. 3 where the value of  $k$  is 0.21, and it follows from equation (13) that the final stress  $S_\infty$  is  $1.21 \times 19.7 = 23.8$  tons/in.<sup>2</sup>. The curve shown in Fig. 4 was not drawn through the experimental points, but was calculated from these constants, using equation (10) such that :

$$R = \left( \frac{23.8 - 3.0}{23.8 - S} \right)^{0.21}$$

Except at low stresses, all the experimental determinations lie very close to this calculated curve.

A similar investigation of phosphorus-deoxidized copper gave almost identical results, shown as white circles in Fig. 4. In this case, however, the departure from the equation at low stresses was rather more marked.

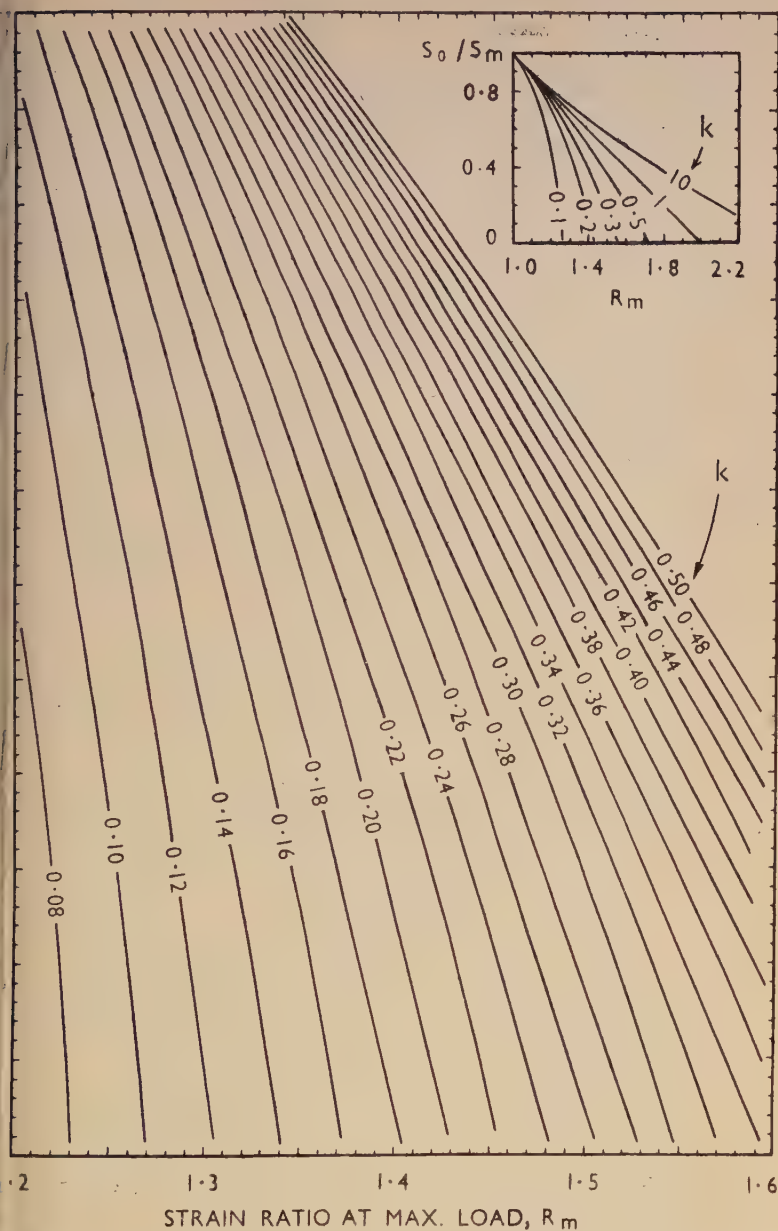


Fig. 3.—Determination of  $k$  from True Stress and Strain Ratio at Maximum Load.

$$R_m = \left\{ \frac{1}{k} \left( k + 1 - \frac{S_0}{S_m} \right) \right\}^k$$

Fig. 5 shows curves for O.F.H.C. copper annealed at 600° C. and tested at 1°, 18°, and 43.5° C., respectively. The curves are those calculated from the constants noted under Fig. 5, while the points represent the experimental data, obtained in this case from autographic load extension diagrams. None of the experimental points lies more than 0.01 on the strain-ratio axis from the curve, and this is considered to

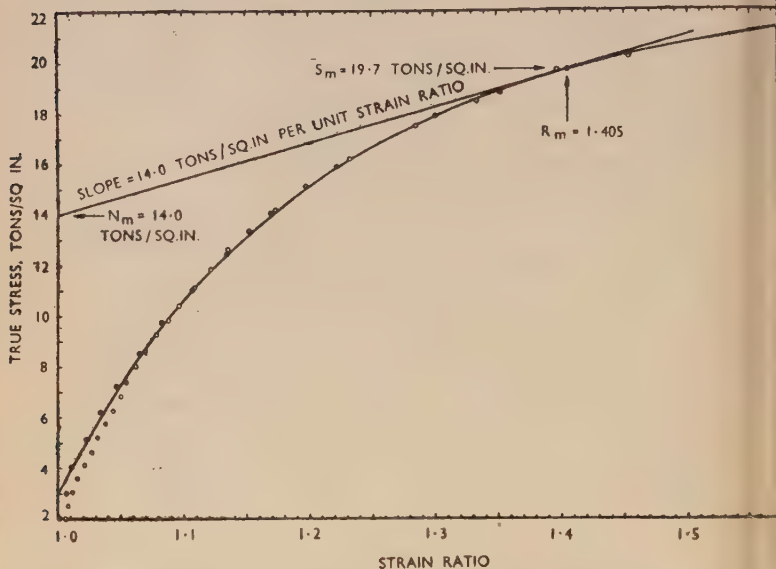


FIG. 4.—Tensile Tests on Electrolytic and Phosphorus-Deoxidized Coppers. The curve represents the equation:

$$R = \left( \frac{S_{\infty} - S_0}{S_{\infty} - S} \right)^k, \text{ where } S_{\infty} = 23.8 \text{ tons/in.}^2$$

$$S_0 = 3.0 \text{ tons/in.}^2, k = 0.21.$$

#### KEY.

Black circles = Experimental results for electrolytic H.C. copper.

White circles = Experimental results for electrolytic deoxidized copper.

within the experimental error of the autographic diagrams. There is a progressive fall in all the constants with increasing temperature.

Three similar curves for sand-cast  $\alpha/\beta$  brasses are given in Fig. 6, and again there is satisfactory agreement of the calculated curves with the experimental data. From the constants noted under the diagram it can be observed that both the final stress and the index diminish as the concentration of elements other than copper and zinc is raised. The effect of the additions is to diminish the uniform elongation prior to necking.

$S_m$  and to increase the ratio of the initial stress to that at the maximum and  $S_0/S_m$ . It has already been pointed out that, according to Fig. 3, a diminution of  $R_m$  reduces the value of  $k$  more rapidly than it is raised by an increase in  $S_0/S_m$ ; the final stress  $S_\infty$  follows the index according to equation (13).

Fig. 7 shows curves for three annealed steels taken from the work of

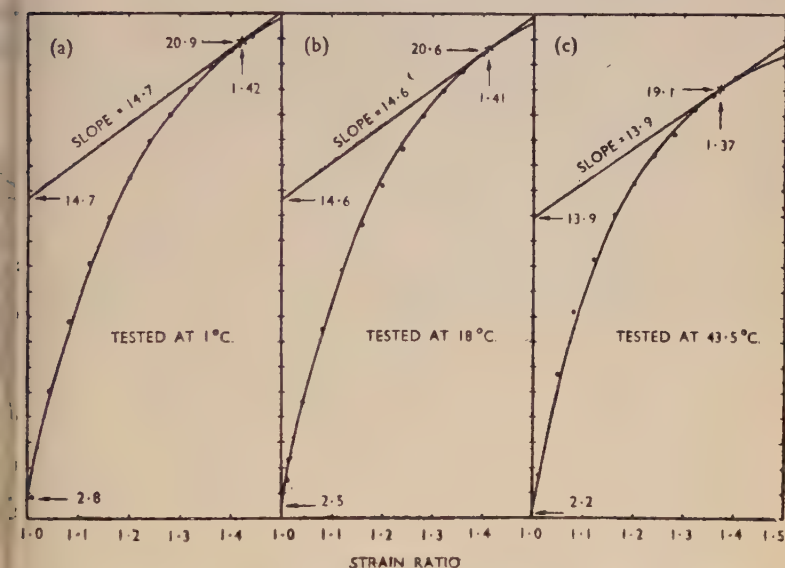


Fig. 5.—Tensile Tests on Oxygen-Free High-Conductivity Copper at Different Temperatures.

(a)	(b)	(c)
$S_\infty = 25.5$ tons/in. <sup>2</sup>	$S_\infty = 25.0$ tons/in. <sup>2</sup>	$S_\infty = 22.3$ tons/in. <sup>2</sup>
$S_0 = 2.8$ "	$S_0 = 2.5$ "	$S_0 = 2.2$ "
$k = 0.22$	$k = 0.21$	$k = 0.17$

MacGregor,<sup>3</sup> the values obtained for the initial and final stresses and the index being those given beneath the diagram. In each case the index was distinctly smaller than for the copper alloys previously considered, and its value was identical for the two mild steels, the other properties of which differed appreciably.

Data for an annealed low-carbon steel from the work of Mehringer and MacGregor<sup>4</sup> are reproduced in Fig. 8. The left-hand part of the diagram shows strain ratio as a function of true stress; it demonstrates the excellent agreement between the experimental observations and calculated curve while the deformation remains homogeneous, and the



wide divergence between them under conditions involving necking. The index  $k$  was found to be the same as for the two mild steels of Fig. 7, though the strength was considerably greater.

The same curve is given on the right of Fig. 8 using logarithmic strains as abscissæ, and reveals the linear relationship between stress and strain during necking observed by MacGregor. He claims that proportionality

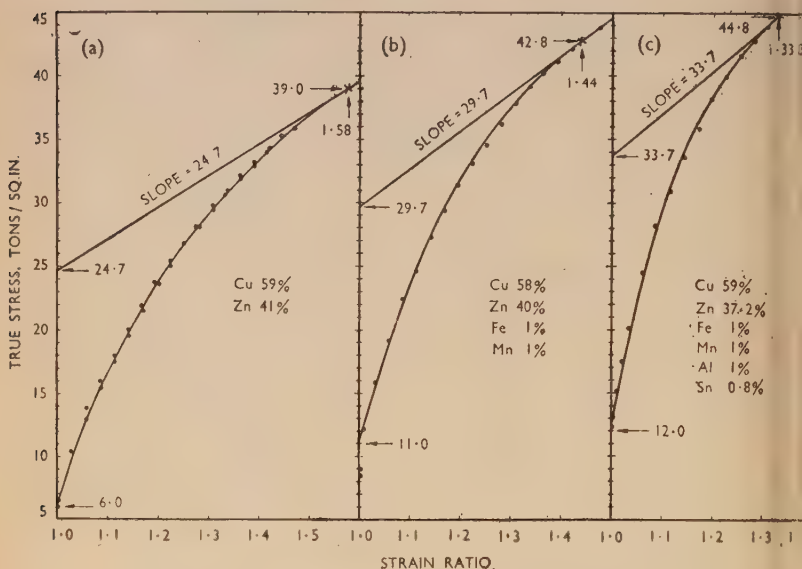


FIG. 6.—Tensile Tests on Cast  $\alpha + \beta$  Brasses.

(a)	(b)	(c)
$S_{\infty} = 55.0$ tons/in. <sup>2</sup>	$S_{\infty} = 54.8$ tons/in. <sup>2</sup>	$S_{\infty} = 52.4$ tons/in. <sup>2</sup>
$S_0 = 6.0$ "	$S_0 = 11.0$ "	$S_0 = 12.0$ "
$k = 0.41$	$k = 0.28$	$k = 0.17$

begins at the point on the curve corresponding to the maximum load. If this were true, it would necessarily follow from equation (7) that the slope of the line must be numerically equal to the true stress at the maximum load, namely 35.8 tons/in.<sup>2</sup> in the present instance. It is evident from the diagram, however, that the actual slope is only about two-thirds of the required value, and the same is true of all MacGregor's curves. Linearity, if it really exists, does not commence at the maximum load, but at a point appreciably above it where the slope of the curve (plastic modulus) is less. It should be emphasized that this conclusion is a geometrical necessity quite independent of the equation proposed in this paper. The mode in which the allegedly linear portion of the curve

comes up with that of homogeneous tension is by no means clear, but on the assumption that deformation remains sensibly homogeneous up to a critical stress somewhat above the maximum load, the value of such critical stress can be derived from the slope of the subsequent line by the use of equation (12), namely  $P = (S_{\infty} - S)/k$ .

If it is true that tensile deformation remains sensibly homogeneous

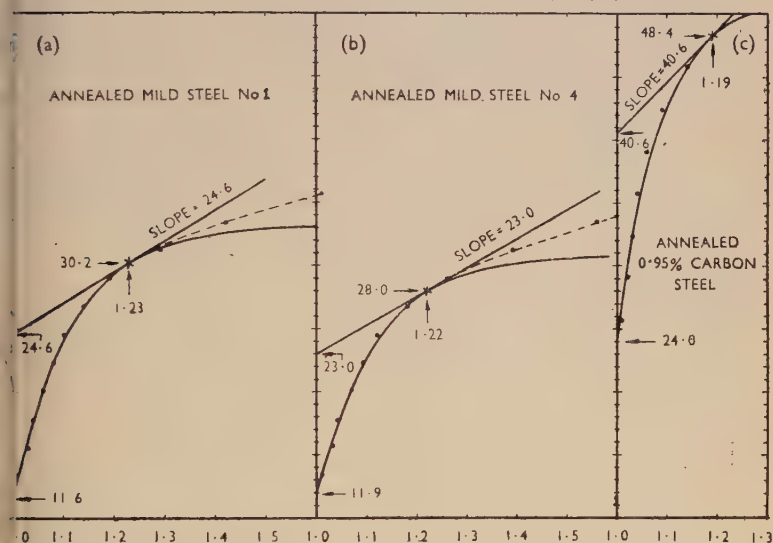


FIG. 7.—Tensile Tests on Steels (MacGregor).

(a)	(b)	(c)
$S_{\infty} = 33.5 \text{ tons/in.}^2$	$S_{\infty} = 31.1 \text{ tons/in.}^2$	$S_{\infty} = 52.8 \text{ tons/in.}^2$
$S_0 = 11.6$ "	$S_0 = 11.9$ "	$S_0 = 24.0$ "
$k = 0.11$	$k = 0.11$	$k = 0.09$

to stresses appreciably above the necking point, this opens up the possibility of carrying a tensile test to incipient fracture under homogeneous conditions. A specimen could be pulled until necking just began, machined to remove the neck, and again tested until perceptible necking occurred. The second neck would be unlikely to form in the region of prior work-hardness caused by the first, but continued alternation of pulling and machining would eventually work-harden the whole of the gauge length to the same extent. After this stage, persistence with the process would allow a new section of the stress-strain curve to be entered and investigated. By such procedure the whole of the curve to incipient fracture could be determined under conditions of almost complete

homogeneity, recognizing, however, that the repeated interruptions might influence the results.

Though opportunity to carry out the experiment just described has been lacking, a different approach to the problem has been tried. This is based on the finding of Haigh and Jones <sup>5</sup> that longitudinal stresses alone, free from radial components, act upon the plane part-way along

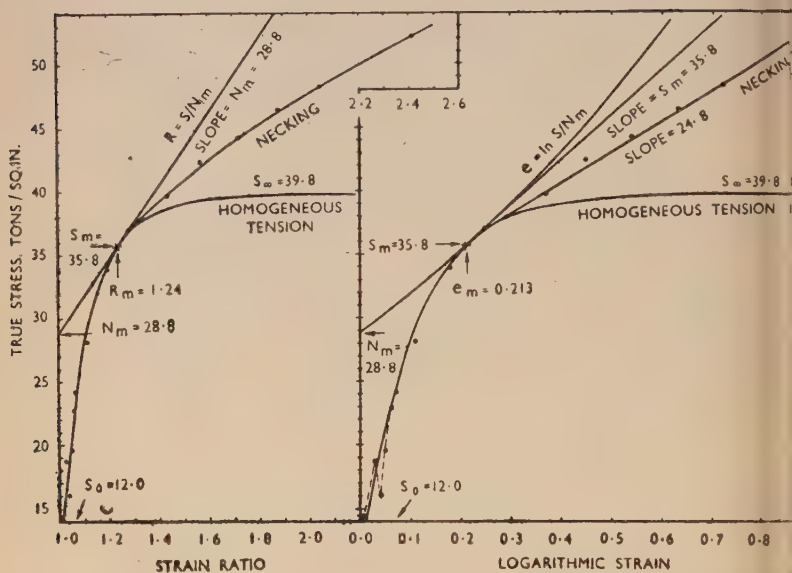


FIG. 8.—Tensile Tests on Annealed Low Carbon Steel (Mehringer and MacGregor)

$$S_{\infty} = 39.8 \text{ tons/in.}^2$$

$$S_0 = 12.0 \quad "$$

$$k = 0.11 \quad "$$

the neck where the curvature of the surface changes from convex to concave. In this region, therefore, the deformation is homogeneous.

Tensile stress-strain curves were available for samples of copper containing 0.25% phosphorus, both in the annealed condition and after 50% reduction of sectional area by cold drawing (strain ratio = 2.00). The diameter of the specimens was 0.357 in., giving an initial sectional area of 0.100 in.<sup>2</sup> During the tests, photographs of the profile of the neck had been taken at a series of known loads. These photographs were enlarged to exactly 10 times the dimensions of the specimens, and measurements were made of the diameters at intervals of 0.02 in. along the length of the neck. The minimum diameter at the centre of the neck was thus obtained directly, while the plane of change of surface curvature

ould be located as that at which the change of diameter per 0.02 in. of length was at a maximum.

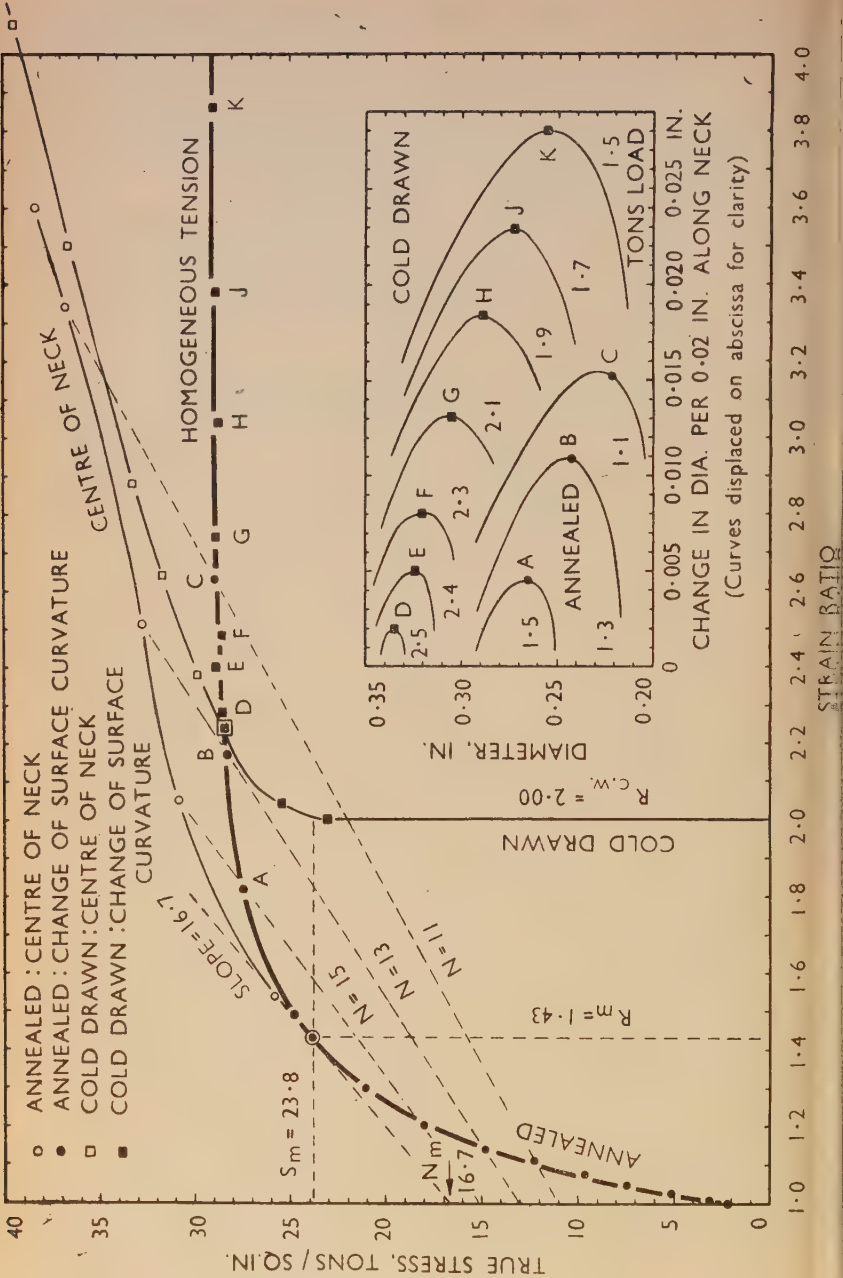
As shown by the heavy curve in Fig. 9, the data for the annealed material up to the maximum load agreed closely with the proposed equation, the parameters being  $S_0 = 2.2$  tons/in.<sup>2</sup>,  $S_\infty = 29.1$  tons/in.<sup>2</sup>, and  $k = 0.22$ . This curve was extrapolated mathematically to deformations beyond the necking point, as indicated in the diagram.

The stress-strain relationships derived from the minimum sectional area at the centre of the neck are plotted in Fig. 9 as white circles and squares for the annealed and cold-worked materials respectively. The curves so defined have an upward trend due to secondary radial stresses and show no indication of eventually reaching a steady stress.

After passing the necking point, the stress on the un-necked portion of the specimen falls continuously with the diminishing load, while that at the centre of the neck increases progressively, as just described. The calculated curve for homogeneous deformation, however, rapidly approaches a constant stress which is intermediate between these values. It is apparent, therefore, that at some position along the neck the stress must be equal to that defined by the basic curve, and the crucial requirement of the experiment is to ascertain whether or not the position at which this equality occurs coincides with the plane of change of surface curvature, where, according to Haigh and Jones, the operative stress is pure homogeneous tension.

The point on the basic curve defined by any particular nominal stress can be determined by the simultaneous solution of equations (2) and (10), or more simply by the equivalent geometrical construction outlined in the appendix. According to this, the required point can be located by the intersection of the basic curve with a straight line drawn from the origin having a slope equal to the nominal stress in question. Such lines for the nominal stresses appropriate to the available photographs are shown in Fig. 9 for the annealed specimen, but those for the cold-worked material have been omitted to avoid confusion. From the strain ratios so found, diameters were calculated, and the location of these in relation to the contour of the neck is illustrated in the insert to the diagram. It is apparent that the diameters which satisfy the basic curve correspond with those at which the rate of change of diameter with respect to length is at a maximum, i.e. with the position in the neck at which the change of surface curvature occurs. The experiment therefore provides evidence that the basic equation proposed in this paper is applicable to tension under homogeneous conditions, even when the necking stress is exceeded.





## VI.—THE EFFECT OF PRIOR DEFORMATION.

If a stress  $S_1$  is homogeneously applied to an annealed specimen the original area of which is thereby changed from  $A_0$  to  $A_1$ , the strain ratio

$$R_1 = \frac{A_0}{A_1} = \left( \frac{S_\infty - S_0}{S_\infty - S_1} \right)^k$$

for any higher stress  $S_2$  the conditions will become :

$$R_2 = \frac{A_0}{A_2} = \left( \frac{S_\infty - S_0}{S_\infty - S_2} \right)^k$$

relative to the dimensions of the specimen in its pre-strained state, however, this second strain ratio would be :

$$R'_2 = \frac{A_1}{A_2} = \frac{A_0}{A_2} \cdot \frac{A_1}{A_0} = \left( \frac{S_\infty - S_1}{S_\infty - S_2} \right)^k \quad . \quad . \quad . \quad (15)$$

Equation (15) is identical with the basic equation (10) except for the substitution of  $S_1$  for the threshold stress  $S_0$ , and therefore accords with the well established fact that if a specimen is loaded to a definite stress, unloaded, and re-tested, it yields at a stress approximating to that which was first applied.

The same argument is applicable to cold-working operations in so far as they can be regarded as taking place under homogeneous conditions. Cold drawing is similar in character to tension, and the author, among others, has shown <sup>6</sup> that strains due to drawing can be combined with those of a subsequent tensile test to form a continuous stress-strain curve. At the same time it was pointed out that after drawing to strains greater than the uniform tensile elongation, defined by  $R_m$ , the necking stress  $S_m$  takes the place of the normal "yield point". Both these considerations are illustrated in Fig. 9. Firstly, the tensile strains on the cold-drawn copper-phosphorus alloy have been combined with the drawing strain by the simple expedient of multiplying by the strain ratio involved in the drawing process, namely 2.00, and secondly, it is apparent from the diagram that, when so combined, the homogeneous curve for the cold-drawn material merges with that for the annealed material as the necking stress, marked by the enclosed square, is reached. The *apparent* yield point of the cold-drawn sample was approximately equal to the original necking stress in the annealed material, marked by the enclosed circle.

It should be made clear that heavily cold-worked materials can support stresses in excess of the final stress  $S_\infty$  which characterizes homogeneous deformation.

## VII.—CONDITIONS AT LOW STRESSES.

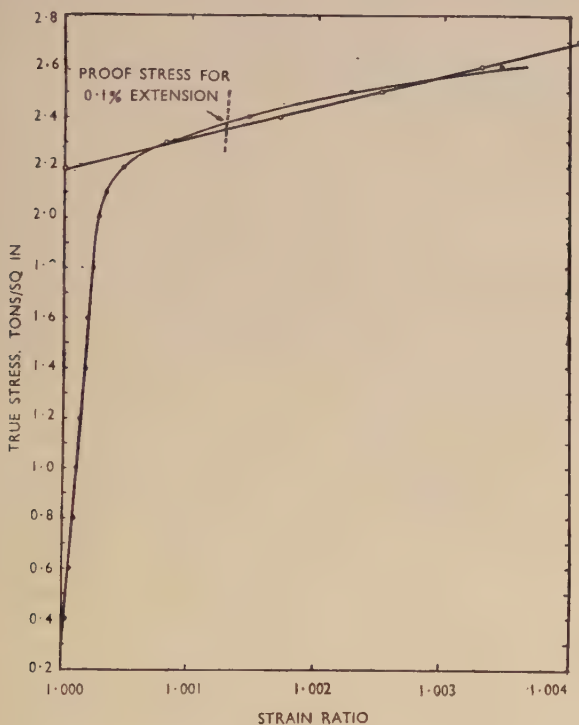
It is evident from the form of the equation proposed in this paper that no provision is made for linkage with the elastic line. While Osgood, in the review mentioned in the Introduction, discredited any equation for which the initial slope was other than Young's modulus, there seems to be little reason for doing so, because elastic and plastic behaviour are essentially different. Moreover, for any polycrystalline material the transition from the condition in which all the crystals are deforming elastically to that in which all are deforming plastically is likely to be ill-defined, for it is improbable that all the crystals would undergo the change simultaneously. Thus, a transition region may be expected in which an ever increasing proportion of the crystals is passing from the elastic to the plastic régime. The chance of any particular crystal commencing to behave plastically is influenced by numerous factors, such as its shape and size as well as its orientation in relation both to the direction of the prevailing stress and to the orientation of the crystals around it. If it is further conceded that in local regions stresses may be built up in excess of the threshold stress for plastic deformation, even though the applied stress remains below that value, it is not surprising that no satisfactory mathematical expression has yet been evolved for the stress-strain curve during the transition stage.

The threshold stress for plastic deformation  $S_0$  is essentially the stress at which the specimen would begin to deform plastically in the absence of elastic strain, and on the assumption that all the crystals were simultaneously affected. It differs from any normally determined proof stress or yield point in that it is not located on the experimental stress-strain curve, but is the result of extrapolating the main trend of the plastic curve backwards to zero deformation behind the elastic line. Generally, however, it approximates to the normal 0.1% proof stress, as illustrated in Fig. 10, in which an extensometer test on the copper-0.25% phosphorus alloy already described is compared with the lower portion, on an enlarged scale, of the curve for plastic deformation shown in Fig. 9.

From the foregoing it is apparent that the proposed equation presents an idealized picture of plastic deformation at low stresses, and does not accurately reflect the true physical behaviour of materials under such conditions. This, however, does not impair its usefulness in connection with cold-working and other problems involving relatively large deformations.

## VIII.—SUMMARY AND CONCLUSIONS.

From the work of Cook and Larke the inference is drawn that under homogeneous compression a condition is ultimately reached in which the specimen deforms under constant stress. Thus, the difference between this final constant stress and the threshold stress at which deformation



10.—Extensometer Test on Annealed Copper Containing 0.25% of Phosphorus.

## KEY.

Black circles = Experimental determinations.

White circles = Points calculated from the constants given under Fig. 9.

It begins to define the total capacity of the material to accept stress capable of producing homogeneous plastic deformation. Similarly, the difference between the final constant stress and any particular stress above the threshold value is the stress capacity which remains available after the application of the stress in question.

Defining the modulus of plasticity (comparable with the modulus of



elasticity) as the instantaneous rate of change of true stress with respect to true (logarithmic) strain, it is shown that for the homogeneous compression tests of Cook and Larke *the modulus of plasticity at any instant is proportional to the available stress capacity.*

Using the symbols given on pp. 539-540, the equation expressing this relationship is :

$$P = \frac{dS}{de} = \frac{C}{k} = \frac{S_{\infty} - S}{k}$$

which in integrated form becomes :

$$e = \ln \frac{L_0}{L} = k \ln \frac{C_0}{C} = k \ln \left( \frac{S_{\infty} - S_0}{S_{\infty} - S} \right)$$

or alternatively :

$$R = \frac{L_0}{L} = \left( \frac{C_0}{C} \right)^k = \left( \frac{S_{\infty} - S_0}{S_{\infty} - S} \right)^k$$

It is further shown that the same relationship is applicable to a number of tensile tests on copper alloys and steels, provided that the deformation remains homogeneous, not only up to but beyond the point at which necking commences. Methods are adduced for determining the parameters of the equation from an ordinary tensile test, and it might be added that such basic information can be obtained in this way more expeditiously and with greater precision than from the homogeneous compression test devised by Cook and Larke. A single specimen instead of three or four is all that is required, and no extrapolation is involved.

The proposed equation accords with the well known fact that the threshold stress for the plastic deformation of a previously strained material corresponds with the true stress applied in the pre-straining operation.

While the equation idealizes the conditions at low stresses and does not embrace the fillet with which the plastic curve merges into the elastic line, this does not detract from its potential usefulness in connection with problems involving larger deformations.

At stresses above the maximum load or necking point in tension, the equation defines the curve which might be expected if fully homogeneous conditions were achieved in this region. This has been verified by recourse to the finding of Haigh and Jones that pure homogeneous tension operates on the plane part-way along the neck where the curvature of the surface changes from convex to concave.

It is suggested that the basic curve could be used as a standard of reference in assessing the degree of internal friction (inhomogeneity) characterizing normal cold-working operations.

The substance of this paper is put forward tentatively on meagre

vidence in the hope of stimulating further research. The effects of such factors as temperature and strain rate have not, for instance, been studied. Though agreement of the equation with the experimental data was satisfactory in the cases investigated, the evidence is insufficiently comprehensive to establish proportionality between the plastic modulus and the available stress capacity as a fundamental principle of homogeneous deformation.

#### ACKNOWLEDGEMENT.

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#### APPENDIX.

##### SOME GENERAL PROPERTIES OF STRESS-STRAIN CURVES.

The properties of stress-strain curves outlined in this Appendix are of general applicability and make no assumptions in regard to the mathematical form of the curve. They are well established and are merely given here for the convenience of readers who may be unfamiliar with them. Two cases will be considered, using strain ratios and arithmetic strains as abscissæ, respectively.

##### *Case 1. Strain Ratios.*

By equation (2)  $N = S/R$ , and it follows that the condition of maximum nominal stress (maximum load or necking point) is such that :\*

$$dN = \frac{S_m dR_m - R_m dS_m}{R_m^2} = 0$$

Since by definition the strain ratio is never less than unity, the denominator is not equal to zero, and therefore :

$$\left( \frac{dS}{dR} \right)_m = \frac{S_m}{R_m} = N_m \quad . \quad . \quad . \quad . \quad (16)$$

\* The quantity in respect of which this differentiation is performed need not be stated for present purposes, since it would obviously cancel out in equation (16).

Thus the slope of the curve, at the maximum load, when strain ratios are used as abscissæ, is numerically equal to the ordinary tensile strength  $N_m$  of the material.

This is illustrated geometrically in Fig. 11, in which any straight line drawn from the origin satisfies equation (2), the slope of the line being

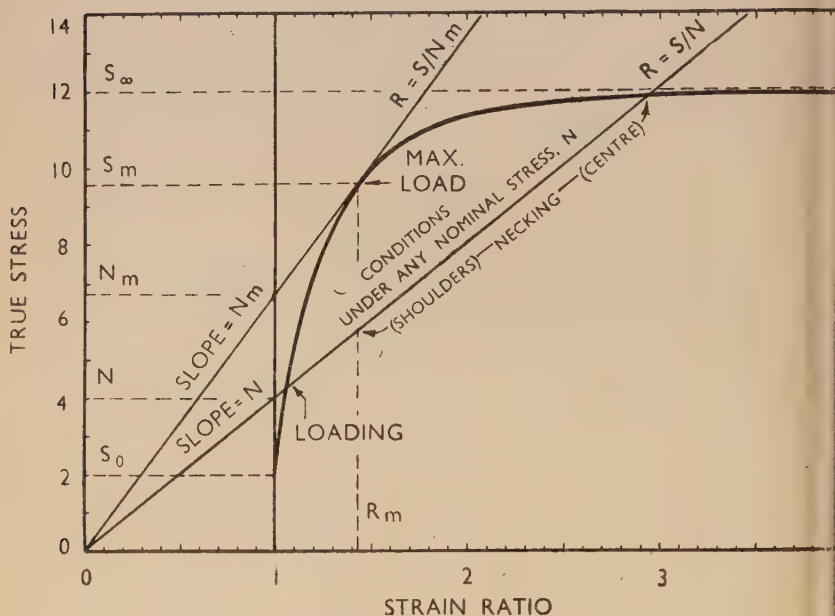


FIG. 11.—Stress-Strain Relationships Using Strain Ratio.

$$\begin{aligned} S_\infty &= 12 \text{ stress units} \\ S_0 &= 2 \text{ " " } \\ k &= 0.25 \text{ " " } \end{aligned}$$

$$\begin{aligned} N_m &= 6.72 \text{ stress units} \\ S_m &= 9.60 \text{ " " } \\ R_m &= 1.43 \text{ " " } \end{aligned}$$

the applied nominal stress  $N$ . Such a line can therefore be used to indicate the variations of true stress from point to point along a specimen, the sectional area of which may vary owing to necking or other causes, while it is subjected to the constant nominal stress  $N$ .

The slope of the straight line is clearly at a maximum when it becomes the tangent to the curve, and the tangent therefore defines the conditions at the maximum load; its slope is the nominal tensile strength  $N_m$ , while the co-ordinates of its point of contact with the curve are, respectively, the true stress  $S_m$  and strain ratio  $R_m$  at the maximum load.

## Case 2. Logarithmic Strains.

Similar considerations apply when logarithmic strains are employed, but in this case it is necessary to take the logarithmic form of equation (2), namely :

$$\ln N = \ln \frac{S}{R} = \ln S - \ln R = \ln S - e \quad . \quad . \quad (17)$$

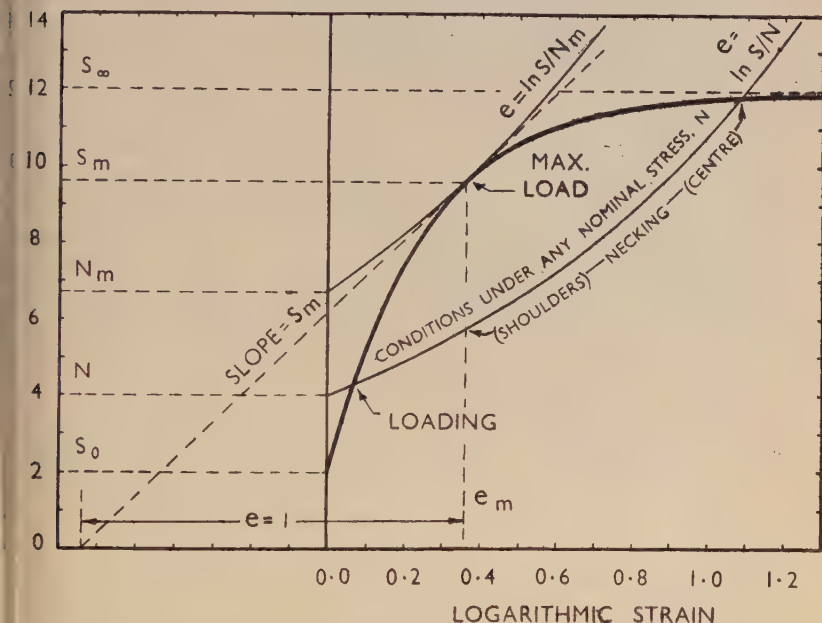


FIG. 12.—Stress-Strain Relationships Under Logarithmic Strain.

$$S_{\infty} = 12 \text{ stress units}$$

$$S_0 = 2 \quad , \quad ,$$

$$k = 0.25 \quad , \quad ,$$

$$N_m = 6.72 \text{ stress units}$$

$$S_m = 9.60 \quad , \quad ,$$

$$e = 0.358 \quad , \quad ,$$

Since the maximum nominal stress coincides with the maximum value of its logarithm, it is apparent that this maximum is defined by :\*

$$d(\ln N) = d(\ln S_m) - de_m = \frac{dS_m}{S_m} - de_m = 0$$

\* The quantity in respect of which this differentiation is performed need not be stated for present purposes, since it would obviously cancel out in equation (16).

N.B.—The relationships illustrated in Figs. 11 and 12 do not depend on the equation of the stress-strain curve, which, however, has been drawn to satisfy

$$e = \left( \frac{S_{\infty} - S_0}{S_{\infty} - S} \right)^k.$$



whence :

$$\left(\frac{dS}{de}\right)_m = S_m \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

which shows that under these conditions of plotting the slope of the stress-strain curve at the maximum load is numerically equal to the true stress at the maximum load.

In Fig. 12, which depicts this relationship, the variation of true stress along a necked specimen under a fixed nominal stress is shown by curves corresponding to equation (17), such that :

$$e = \ln S - \ln N.$$

Of a nest of such curves for different values of the nominal stress  $N$ , that which represents the maximum nominal stress or ordinary tensile strength  $N_m$  must touch the stress-strain curve proper at a point of which the co-ordinates are  $S_m$  and  $e_m$ . Moreover, the slope of the two curves must be identical at this point of contact between them, and it follows from equation (18) that this common slope is numerically equal to the true stress at the maximum load  $S_m$ .

MAY LECTURE, 1948.

## THE SEARCH FOR MINERALS BY PHYSICAL METHODS. 1136

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## SYNOPSIS.

A general account is given of the ways in which physical measurements performed with suitable instruments on the earth's surface may help to discover what lies buried beneath. It is shown how this practice, known as geophysical prospecting, has been the means, in co-operation with economic geology, of determining the location and depth of potentially oil-bearing rock structures, so that drilling for oil production may be undertaken with greater assurance of success. The various available methods—gravitational, magnetic, seismic, and electrical—are described in outline and the applicability of each to the problems encountered is discussed. The actual operation of gravitational and seismic surveying is treated in greater detail, with general remarks on the instruments employed. Emphasis is laid on the search for oil, this being at present the field in which geophysical work has found the greatest scope, with the gravitational and seismic methods as the principal modes of investigation. The possibilities of geophysical prospecting for minerals other than oil are also touched on.

## I.—INTRODUCTION.

WHEN I was honoured by the invitation from your President to deliver this May Lecture, he suggested at the same time that I should speak about geophysical prospecting. It seemed likely to me that he had in mind the particular branch of this subject which relates to the search for mineral ores—the raw material for the production of metals. I therefore hesitated, partly because the application of physics in this direction has not yet progressed very far, but chiefly because my lack of practical experience in the matter would make it impossible for me to discourse worthily on it on such an important occasion as this. Accordingly, I told your President that I should like to devote the lecture mainly to the search for oil by physical methods, and he assured me that by doing so I should not render what I had to say inappropriate. I shall thus be on more familiar ground, and able to draw on my own experience during many years and on the knowledge I have derived

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from frequent visits abroad to observe the operation of geophysical methods in actual practice. Moreover, I shall be dealing with a subject of much wider scope—one indeed that has developed in practice so rapidly during the last thirty years as to become of quite major importance in its fields of application.

## II.—ORIGIN AND BASIS OF GEOPHYSICAL PROSPECTING.

But first I wish to say something in general about geophysical methods in relation to prospecting for minerals, and how it comes about that there is in certain directions such an increasing demand for their use. Very little was heard about these methods until the beginning of the present century. Until then, presumably, minerals were being found in the earth's crust in adequate quantities by simpler and more obvious processes. Where the mineral ore itself outcropped at the earth's surface, nothing more than visual observation was needed; and the productive area could be followed underground by digging in an intelligent manner and by drilling test holes to shallow depths in the immediate neighbourhood. Or, in the case of mineral oil, which occurs impregnating certain porous sedimentary rocks of suitable structural form, copious seepages visible at the surface, supplemented by indirect geological evidence, gave reasonably reliable guidance to hidden reservoirs of oil. These, not being very deep underground, could be exploited successfully without undue expense in drilling. Naturally, the minerals that could thus be won easily and profitably have been won first, and, as they gradually approached exhaustion, the need for prospecting at increasing depths became progressively more and more urgent, especially as the demand for greater output was increasing at the same time. Ultimately, of course, the tests have to be made by drilling, the cost of which is more than proportionate to depth. The difficulty is not one of impracticability, for drilling technique has now advanced so much that holes more than three miles deep can be bored successfully, but one of expense, which cannot be recouped if the result proves negative. And that is just what is liable frequently to happen owing to uncertainty as to the correct location for the hole. The deeper the objective—for example, an oil-bearing rock structure—the less reliable does the geological evidence derived from surface observations become. Moreover, in some cases, geological guidance is entirely lacking owing to the absence of any surface features at all, as in flat desert country.

It was this dilemma in the search for minerals and rock structures at increasing depths underground that led to the call for physical

methods, involving measurements at ground level, to detect and delineate what lay underneath. Could not use be made of the variation of the physical properties of the components of the earth's outer crust in such a way that buried ore bodies or rock structures would reveal their situation either automatically or under the stimulus of suitable physical operations carried out on the surface? I feel sure that it is not necessary for me to stress the fact that I am not referring now to divining, and that I shall not be expected to enter at all into the controversy which has always surrounded this mysterious subject. We are concerned now with prospecting methods based on well established physical principles, and on the well known physical properties of the objectives sought. A notable case of successful operations of this kind was already on record, namely the discovery of large buried deposits of iron ore, simply by the marked magnetic effect which they produced. No very delicate instruments were required for the purpose; ordinary compasses sufficed. The largest such magnetic anomaly known is at Kursk in Russia, and the effect at ground level is so great in places that a compass needle actually reverses its direction, pointing south instead of north. This remarkable magnetic anomaly originates from an enormous ore body 150 metres deep, estimated at 20,000 million tons and consisting largely of the oxide of iron known as magnetite. Other similar deposits occur in Sweden, where, also, relatively crude magnetic observations are employed and found effective for prospecting. In practice the method is of very limited application, since it is confined to large concentrations of magnetite, the magnetic behaviour of which is quite exceptionally strong. But it serves at least as an illustration of the geophysical approach to prospecting—the observation and measurement of real physical effects produced by the particular character of the objectives underground.

### III.—OUTLINE OF THE PRINCIPAL GEOPHYSICAL METHODS :

#### GRAVITATIONAL, MAGNETIC, ELECTRICAL, AND SEISMIC.

On the broader aspects of the subject, more especially in relation to the search for oil, activity in geophysical prospecting in response to the call I have mentioned can be said to have started just after the first World War. Since then four principal methods have been developed, about each of which I propose to give a brief outline before dealing more particularly with two of them which have greatly outstripped the others in practical application.

There is first the method which depends on the gravitational forces which all material bodies exert whatever their magnitude. Each part



of the earth, for example, however small, makes its contribution to the total gravitational pull experienced at the surface. If the whole earth were of uniform density, each unit volume of it would contribute a force depending merely on its situation with respect to the point of measurement, and there would be nothing to differentiate one part from another. But if, as is actually the case, the various rocks composing the earth's crust are of different densities, and are distributed in a non-uniform manner, there will be local variations produced—gravitational anomalies as they are called—due to the fact that the denser rocks are more effective gravitationally. The variations of force encountered in practice are extremely small—I shall give examples later—and the instruments used for measurement have to be of great sensitivity. But given such instruments the gravitational method of geophysical surveying simply consists of using them to carry out systematic surveys with a view to finding gravitational anomalies likely to be associated with underground structures of economic value. The method has, in fact, turned out to be of wide applicability and of great importance in the search for oil fields.

Secondly, we have the magnetic method, already mentioned as a crude device but now refined so as to have wider scope. All substances are capable of being magnetized to a certain degree, and the susceptibility in this respect varies from one to another. Consequently, the components of the earth's crust have become magnetized to different extents by the earth's main magnetic field. Thus magnetic anomalies are produced at the earth's surface in those regions where bodies magnetized to a degree greater or less than the average lie underground. The question of whether or not these anomalies can be observed depends on the sensitivity of the measuring instruments available. Great progress has been made in recent years in the development of sensitive magnetometers, and in consequence the magnetic method of survey has become useful not merely for defining very large anomalies like that at Koursk, but for locating ore bodies both much smaller and much less magnetic. It is, however, probable that the method will continue to be limited to the location of ore bodies and rock structures containing considerable quantities of those exceptionally magnetic materials which we know as ferromagnetic substances.

These two methods—the gravitational and the magnetic—are distinguished from the remaining two by being, as we might say, passive. In both we simply make tests of certain physical conditions as they occur naturally on the earth's surface, and deduce what we can from the observations. In the other cases, action is required. We have to apply a suitable stimulus to the earth and observe the response

by appropriate means. Nevertheless, each method is again based on differences of particular physical properties of the materials lying underground. In the electrical method, in the practice of which there are several variations of field procedure, successful operation depends on there being a sufficient difference of electrical conductivity as between the object of search and its surroundings. If we have, for example, an ore body which is a good conductor compared with the ground in which it lies buried, and if we introduce into the ground artificially from a suitable source a current of electricity, the lines of current flow will become concentrated in the highly conducting ore body at the expense of the material enveloping it. Thus the pattern of current flow will assume a form different from what it would be with no ore body present. This difference may be detected, and the ore body thereby located, by suitable tests carried out on the earth's surface.

The most usual method employed is to survey the surface by means of probing electrodes inserted in shallow holes in the ground and connected to a galvanometer. If the artificial current used is direct it is passed into the earth by main electrodes which are widely separated over the region under test. A variant is to work with alternating current, in which case electrodes may be dispensed with. Coils of wire not connected with the earth may then be used instead, both to provide the artificial current stimulus by electromagnetic induction and to detect the response by the same process.

It should be noted that electrical methods, although primarily devised for assisting in the location of metalliferous ore-bodies, are not necessarily limited thereto in application. Deficiencies of electrical conductivity as well as excesses can also provide a basis of use in practice, and some advances in the elucidation of underground rock structure are, in fact, being made in this respect.

I come now to the last of the four main geophysical methods I am attempting to outline, namely, what is known as the seismic method. It is operated in more than one way, but each depends on the same physical properties of the contents of the earth's crust. So far it has been applied chiefly—and more widely than any other method—to the examination of the structure of deeply buried sedimentary rocks in relation to the conditions favourable to oil bearing. Broadly, we are here concerned with two physical properties of various rocks—their relative densities and elasticities in combination. The method is closely related to the study of natural earthquakes, known as seismology; indeed, it is seismology on a small scale, using artificial explosions as the controlled stimulus given to the earth, instead of the occasional

earthquake happening without warning. The fundamental measurements involved are the times that are taken by earth tremors in travelling from the explosion to the point of observation elsewhere on the earth's surface. These times, in turn, depend on the various paths by which the tremors proceed and the speeds with which they are propagated in the rock beds traversed by those paths. Now both the paths themselves and the speeds of the tremors are determined by the two physical properties of density and elasticity just mentioned. I do not propose to give here the precise relations, which are, of course, well enough known. It will suffice, I think, to say just two things in this brief outline of the principles of the seismic method. First, that the various beds of rock encountered as we proceed downwards into the earth are characterized by velocities of propagation which change from bed to bed, generally in the sense of increase with depth. And secondly, that, at each interface between successive beds, partial reflection and partial refraction of the earth tremors occurs in a manner similar to the behaviour of light in optics. Both reflection and refraction are used in seismic prospecting; in fact, they are the bases of the two modes of operation. In reflection work we observe what are in effect subterranean echoes of explosions at the surface, not aurally, but by means of seismometers, the tremor-detecting instruments about which I shall have more to say presently. The positions of the explosion and the point of observation being known, and the time elapsing between the firing of the charge and the reception of the echo being measured, the depth of the bed at which reflection occurs can be readily calculated in terms of the average speed of propagation in the superincumbent layers.

An interesting analogy is the procedure adopted in the radio method of determining the heights of the ionizing layers in the upper atmosphere, and its later developments in radar as applied to locating aircraft or even meteorites. The principle is the same; the difference lies in the use of electromagnetic radio pulses instead of mechanical pulses in the earth, and, of course, the region of investigation is upwards instead of downwards.

In the refraction method, the field procedure is much the same as for reflection, but the distance between the explosion and the recording seismometers has to be much greater. It is often used when the reflection method proves to be impracticable. One of the chief difficulties of this latter method is to pick out with certainty from the seismometer record the indications corresponding to reflections from below. All these, having necessarily travelled by longer paths, reach the seismometer later than the disturbance passing directly from the

explosion to the seismometer close to the earth's surface. The effect of this direct pulse is relatively very large and continues for a considerable time, thereby tending to mask the feebler indications of the delayed reflections. The use of refracted pulses under suitable conditions enables this difficulty to be overcome, so that a part of the tremor that has penetrated deeply into the earth actually returns to the surface at distant points and reaches the seismometer *first*. It thus finds this instrument not yet disturbed and gives an indication on the record, feeble it is true, but unconfused, and, therefore, identifiable with greater certainty.

I would like to explain this matter further by asking you to imagine a simple case, that of two horizontal rock beds, so that there is just one interface some distance below the surface of the ground. It is an essential condition that the velocity of propagation in the lower bed should be greater than that in the upper bed—in practice, the greater the ratio is, the better. The energy from an explosion at the surface of the upper bed, that is, at ground level, proceeds in all directions into this bed. Some of it will be reflected at the interface, as we have seen, but some will also penetrate into the lower bed in directions determined by the laws of refraction. At a particular direction of incidence, the so-called critical angle is reached, and, as in the familiar optical analogy, total reflection might be expected to ensue. But this, fortunately, is not strictly true, either in the optical case or in the one we are considering. A small amount of energy does, in fact, enter the lower medium and travels parallel and close to the interface at the higher speed characteristic of this bed. Moreover, as it proceeds, it leaks upwards, as it were, into the upper bed again, reaching the surface at points more and more distant from the explosion until it is exhausted. Thus we have a series of possible refracted paths for the tremor, each consisting of two portions in the upper bed sloping at the critical angle, and a horizontal portion of varying length just within the lower bed. All these refracted paths are, of course, from geometrical considerations, longer than the direct one near the earth's surface, and, if the velocities were the same throughout, the direct pulse would necessarily win the race, as we might say. But this takes no account of the greater speed in the lower bed. It will be clear, I think, that if the length of that part of the refracted path which lies in that medium is great enough, the gain of time thus achieved may more than compensate for the longer total distance traversed. In such cases, the refracted tremor will win, and in practice we indeed find this to be so. As the distance of the recording seismometer is increased, we find at the shorter distances the powerful direct disturbance is the first arrival. A stage is reached,



however, where the weak refracted pulse overtakes the direct one, and beyond that point it actually initiates the trace on the recorder, thus becoming easy to identify. By such measurements the relation between the travel times and the distances between explosion and recorder becomes established. From this we can derive readily not only the values of the velocities in both beds, but the depth of the interface which has been our objective.

#### IV.—PROBLEMS INVOLVED IN THE SEARCH FOR OIL.

I wish now to use the general sketch I have given of geophysical prospecting methods as a background for a more detailed description of the special kind of work with which I have close personal contact: I mean the application of such methods to the search for oil. To do this I must try first to give a picture of what underground oil reservoirs are like, as they exist under the conditions of the present time. You will not expect me, with my very limited knowledge of geology, to say anything authoritative on the origin of this mineral oil and the way it came to be situated where it now is in the earth's crust. But for the development of the picture I ought to mention a few facts relating thereto. It is generally accepted, I believe, that the oil is of marine origin and that the material from which it has been formed was organic matter imprisoned by the sediments gradually deposited in former seas by denudation from neighbouring mountainous land areas. In the course of geological time many thousands of feet of such sediments have been laid down, and the organic material at great depth thus became subjected to very high pressures and elevated temperatures. Under these conditions it changed chemically so as to form oil in the particular bed of mud which it happened to occupy. With the recession of the seas the sedimentary beds consolidated into horizontal layers of rocks of varying porosity and permeability, according to the nature of the particular particles constituting them. Subsequent earth movements sometimes destroyed the horizontal disposition of these layers of sedimentary rock and folded them so as to form hills and valleys—or anticlines and synclines as they are termed geologically. The oil formed at great depth tended to migrate upwards, driven by its great pressure and followed by still deeper salt water on which its lower density caused it to float. It would continue so to migrate slowly through any rocks which were sufficiently permeable until it encountered a bed which was impervious enough to stop further progress. The oil would obviously then accumulate under the arches of the anticlines mentioned, trapped there by the impervious covering bed,

and impregnating the fissures and pores of rock beds immediately below it.

Whether or not this brief outline is a true description of past events, we do know from wide practical experience that oil reservoirs are of the nature indicated. We have, for example, the several great oil fields of Iran—I quote this because I know it best—where each oil reservoir comprises an extensive anticline of porous limestone, a thousand or so feet thick, covered by about a 100 feet of cap rock, as it is called, composed of anhydrite and forming an almost perfect seal against penetration by oil. These underground hog-backs, as we might describe them, are of great dimensions, and the depths of their summits are usually several thousand feet. In length they extend to a dozen miles or more and they are several miles across. Their vertical dimensions vary, but, if at the surface, they would all appear as respectable mountains, and the vertical columns of oil impregnating the limestone flanks are thousands of feet long. Perhaps the most striking way of indicating the importance of these reservoirs is to say that some at least of them are estimated to contain, or to have contained prior to production, several hundred million tons of oil.

Not all oil reservoirs, of course, are on such a grand scale, but they nearly all have this in common, wherever in the world they may be. They are characterized by being sedimentary rock structures of anticlinal or dome-like form, usually sandstones or limestones, in which the oil is sealed by a cover adequately impermeable. And such are the objectives of our search when we set out to examine the possibilities of applying geophysical methods to the elucidation of the problem. But at the very outset I wish to emphasize that this mode of attack ought not to be regarded as an independent one—I mean that, used alone, it is unlikely to achieve much in the way of discovery. It is of the greatest importance that geophysical prospecting should be closely associated with practical geology, so that time and money may not be wasted in surveying barren areas. All the geological evidence available ought first to be taken into account. For example, the folding of the sedimentary beds which has formed a buried anticline is sometimes evident at the surface, and geological examination of the outcropping rocks enables the geologist to deduce approximately the position of the potentially oil-bearing structure at depth. In such a case the function of the geophysicist is to try to locate more precisely the summit of the structure and delineate its shape, so as to fix the points likely to be productive on drilling. Again, where surface evidence is absent owing to the rock folding having been completely covered by water alluvial deposits, thus forming a vast plain area, the geologist

can at least indicate whether or not such hidden folding is likely to exist, and estimate how favourable the conditions are in the region for the occurrence of oil. Geophysical surveying by suitable means would then be carried out only within the limits of area regarded geologically as good. Moreover, constant contact with geological opinion during the actual progress of geophysical work is essential. The surface indications obtained by physical methods are rarely, if ever, sufficient in themselves to solve the problem of what lies underground. Often two or even more interpretations are possible, all of them being equally compatible from the physical point of view, and it becomes necessary to discriminate between them on the basis of geological probability.

We come now to the question of the applicability of the geophysical methods outlined earlier to the special problem of locating oil reservoirs. At first sight it might appear that the method most likely to be effective would be the electrical one, based on the fact that mineral oil is a material of very low electrical conductivity occurring in surroundings which are better conductors. There have been, indeed, some claims of successful operation by this means, but they are not well substantiated. The truth is, I think, that the oil in the underground reservoirs is usually so deep and covered by so many layers of other substances of differing conductivity that the electrical pattern mapped at the surface may become too confused to be capable of interpretation. The volume of the oil itself, moreover, is only a small fraction of that of the rock in which it resides. For these reasons we have to rule out, probably not merely now but for always, the practicability of finding the oil itself by electrical means operated at ground level. The same is true, indeed, of all the potential methods. None of the other physical properties of oil, its relative density, its negligible magnetic susceptibility, or its elasticity, seems at all likely to provide a practical basis for locating it. It has been necessary to turn rather to an indirect approach to the problem, namely to try to discover the rock structures which are likely to be oil reservoirs. This means, of course, that a structure so located will not necessarily contain oil, but the probability of this being so is high enough for the procedure to be acceptable from an economic point of view. What is required of geophysicists is simply that the methods they employ should fix with reasonable precision the situation of rock formations which are *potentially* oil-bearing. And both the considerable achievements in this respect in the past and the world-wide operations at the present time show geophysical prospecting for oil in this indirect manner to have been so well worth-while that it has become essential to the development of the production of oil on sound economic lines. All the four geophysical

methods I have mentioned have been applied to some extent, but electrical and magnetic surveying have played only a secondary role, to which I will make brief reference later. It is in gravitational and seismic work, especially the latter, that the best results have been obtained, and I shall therefore devote most of what remains for me to say to remarks on these two principal methods.

#### V.—APPLICATION OF THE GRAVITATIONAL METHOD.

Firstly, with regard to gravity. The rock structures which are our objective may be expected to give rise to gravitational anomalies at the surface, owing to the fact that the density of this rock usually differs from that of its overburden. Usually, the deeper beds of rock have the greater density, and if in anticlinal form will therefore enhance the gravitational force above them. This generally describes the conditions relating to limestone and sandstone structures, and to find these we have to determine the positions on the surface where gravity is a maximum. The reverse, however, is sometimes true. In many places in the Gulf Coast of the United States, and to a lesser extent in Mid-Europe, the oil reservoirs are associated with so-called salt domes over which the rock folding has been effected by the elevation of great plugs of rock salt from deeper horizons. And the salt is of *less* density than the overlying beds, so that the domes are characterized by minima of gravity above them. The utility or otherwise of the gravitational method must thus be determined largely by our ability to measure the force of gravity with sufficient accuracy to map the anomalies, by means of portable instruments both sensitive and robust enough for field use.

I must try at this point to indicate the quantitative nature of this problem. Quite apart from local anomalies, it is well known that gravity varies over the surface of the earth as a whole, being about 1% less at the equator than at the poles, owing partly to the polar flattening and partly to the effect of the earth's rotation on its axis. On the average, its value is about 980 dynes per gramme, as expressed in C.G.S. units. One of these units is called a gal (as a tribute to Galileo for his early work on gravitation) and one-thousandth part of this is a milligal. Now the total calculated gravitational effect of one of the buried structures we have in mind rarely exceeds a few milligals, and even one or two tenths of a milligal may be significant. The problem therefore is to compare the force of gravity at one point with that at others to an accuracy of one part in ten million of the total attraction exerted by the earth.



Such was the task facing physicists when the question arose of using gravity as a means of surveying for oil-bearing structures round about 1920, which can be taken as the approximate date of the initiation of geophysical prospecting for economic purposes on a significant and growing scale. The usual method of measuring gravity by the timing of pendulum periods achieved an accuracy of several milligals only, and was therefore not sensitive enough for the purposes in view. It then became known gradually to those concerned that the Hungarian physicist Count von Eötvös had many years earlier invented, constructed, and used a portable instrument of quite exceptional sensitivity, which we know nowadays as the torsion balance, for the investigation of gravitational anomalies. And it appeared that, if the claims made for it were as stated, it would serve adequately in the search for salt domes and similar structures.

It is interesting to note that the first torsion balance of this kind was constructed by Eötvös towards the end of last century, just about the same time as Boys in our own country was making his classical laboratory measurements of the constant of gravitation by observing the forces of attraction between spheres of lead and gold, the latter being suspended on a torsion balance quite similar to that which Eötvös used for work in the field.

The long delay in the application of this remarkable instrument to the search for oil can be attributed to two causes. One was that doubts were entertained as to whether it could really function as claimed; doubts which, however, were eventually set at rest, so far as this country was concerned, by tests made at the Science Museum on an instrument specially imported by the Director of that institution. The other reason was the reluctance of Eötvös himself to allow the product of his ingenuity to be used for what he regarded as so base a purpose as commercial gain. Hitherto he and his co-workers had employed it solely in the interests of academic geology. But he was ultimately persuaded against his inclinations, with the result that several new salt domes were discovered, and the activity in the Gulf Coast became at one time so great that about 200 Eötvös balances were in use. It is true that in more recent years the Eötvös instruments have been superseded by others of different construction and greater practical utility. But he has the best claim to be regarded as the father of geophysical prospecting for oil, even if a hesitant one.

These newer instruments for measuring variations of gravity, or gravimeters as they are called, are too numerous for me to describe here except in a general way. In nearly all of them the principle of the spring balance has been adopted. A constant mass is supported

by a spring, and, as its weight varies slightly under the conditions already stated, the spring changes its shape a little, both in length and twist; and from observations of these dimensional alterations the corresponding variations of gravity are deduced. It must be realized that in practice the changes are very small indeed, and that methods of producing large magnification, optical and otherwise, have to be incorporated in order to render them observable. But it is not the necessary magnification which presents the greatest difficulty, for this has been successfully achieved in many ingenious ways. The greatest difficulty has been that of securing sufficient constancy in the physical properties of the material of the spring, especially its elasticity. It was the development and use of metals of the Elinvar type, with their low thermal coefficients of elasticity, that contributed most to solving this problem. Even so, when the instruments come to be used in the field, where they may become subjected to large changes of temperature, it is necessary for them to be enclosed in efficient thermostats to shield them from the effect of such variations.

Several modern gravimeters of various types, but embodying these same principles, have been proved capable of detecting reliably gravity variations of considerably less than one-tenth of a milligal. But they are not so sensitive as the Eötvös torsion balance—yet they are preferred in practice nowadays. May I try to explain this? The Eötvös balance differs somewhat fundamentally from more modern gravimeters in that it measures, not the total value of gravity at a point, but its rate of variation from point to point in a horizontal direction. (I should mention also that it measures other features of the departure of gravity from uniformity which in practice it is desirable to determine.) It consists in essentials of a horizontal beam of aluminium to which are attached at opposite ends and at different levels two equal masses of platinum, the whole being suspended from above by a single wire. Placed in a region where gravity is uniform from point to point, the suspending wire is subject to no torsion. But if the gravitational field is distorted, owing, for example, to the presence of a local geological feature, the differential attraction produced on the two platinum masses gives, under suitable conditions, a twist to the suspending wire which can be observed by optical magnification. The fact that the torsion in this wire is always very small is important, because the requirement of precise constancy of behaviour is not essential, as we have seen it to be for gravimeter springs, subjected as they are to relatively great stresses in supporting the weights. Eötvös thus escaped in the construction of his instrument a major difficulty, probably as a result of deliberate choice on his part, and produced a

practical device which was something like a hundred times more sensitive than the best of modern gravimeters.

But I repeat that, although still in use, it has nevertheless been largely superseded by its less sensitive rivals. One reason for this is that the instrument is very slow in operation, a circumstance which is, indeed, a corollary of its great sensitivity. It has to be set up at the observation point in a particular azimuth, and more than half an hour must elapse before a reading can be taken. Thereafter the azimuth has to be changed several times, with equal delays before observation, which, I should add, is sometimes visual and sometimes by photography. Thus the occupation of a single station is a matter of hours, and two or three stations per day is the most that is practicable. By comparison, modern gravimeters can be operated very much more quickly, a few minutes sufficing to complete observations at one point, and most of the available time can be devoted to transporting the instrument from station to station.

Another objection to the use of the Eötvös balance is its exceptional liability to be influenced by disturbing factors which tend to mask the gravitational effect of the underground objectives sought. Every little surface eminence in the neighbourhood exerts its own gravitational force, and this has to be allowed for as a correction to the measurements before interpretation of the results can begin. Except where the ground surface is nearly flat, this involves a great deal of accurate surface surveying, and if the topography of the country is more than a little rough, the corrections which it is practicable to make in this way become too uncertain to be reliable. The effective use of the balance is thus limited to regions where the ground is plain, or at least with only gently undulating features, such as was indeed the case in the search for salt domes which I mentioned earlier. Modern gravimeters, on the other hand, are much less sensitive to the gravitational effect of surface irregularities, and, although corrections for topography still have to be made, they can be operated successfully in hilly country. In effect, they discriminate between small nearby geological features and great ones at depth in favour of the latter, whereas the torsion balance tends to emphasize the former. This has led to the virtual abandonment of the Eötvös instrument as a means of searching for oil structures at great depth, but I still believe that this remarkable and beautiful device may in the future play new roles in disclosing the presence of ore bodies at shallow depths—a task for which it is so eminently suited.

I have already mentioned that in work with the gravimeters now used, corrections have to be made for topography. The normal gravitational force exerted by the earth decreases with height, owing

to the increase of distance from the earth's centre. This variation with elevation amounts to about 1 milligal in 10 feet. Moreover, the material constituting the eminence at an elevated point itself exercises a force downwards, so that, in comparing the gravitational effects of a deep-seated structure at two surface points of different elevations, this also has to be allowed for. For surface material of average density, a thickness of 30 feet gives rise to a force of approximately 1 milligal. The two effects taken together constitute a diminution of force with height of 0.07 milligal per foot. It will be obvious that if we are to count on 0.1 milligal as being significant in the corrected observations, as I have indicated earlier, very accurate ground surveying as regards elevation must accompany the gravity measurements. There is also the need for surveying in the horizontal plane so as to correct for the normal variation of gravity with latitude, which amounts at its maximum value in latitude  $45^{\circ}$  to 1.2 milligals per mile. And in accurate work, allowance may have to be made, besides, for the small but real gravity variation with time associated with the tidal effects of the sun and moon. For the influence of these, according to their changing positions with reference to the point of observation on the earth's surface, reaches a maximum variation of several tenths of a milligal.

Before leaving the subject of gravity surveying, I ought to say a few words about the conditions of operation in the field. In places where there are good roads or in flat open country with a good surface, the speed of surveying can be very great, because the gravimeters can be transported easily from station to station by motor vehicle. I recall a survey of this nature which I saw in operation in the state of Kuwait at the north-west end of the Persian Gulf. Practically the whole area of this country is flat desert, and the whole of its 5000 or so square miles was surveyed in the course of about seven months during 1937, using only two gravimeters, yet occupying every station on a regular grid pattern of two kilometres interval each way—some 4000 stations in all. And the result was the tracing of a gravity map which gave the first indications of the situation of a great oil field discovered in that country, now in the course of production. But conditions are not frequently as favourable as this. Often very rough and uncharted regions have to be entered, perhaps covered with jungle and traversed by awkward streams. Then the going is much slower, the instruments and other equipment having to be transported by hand. Recently, too, still more difficulties have had to be faced, because the areas of interest in the search for oil have extended to include regions under shallow seas. It says much for the skill and determination of those



responsible that this problem has been attacked with a considerable degree of success, by using diving chambers in which both observer and gravimeter are lowered to the sea bed, and by erecting platforms on which the gravimeter can be operated above sea level.

#### VI.—APPLICATION OF THE SEISMIC METHOD.

I pass now to prospecting by seismic means, which may be said to have made the greatest geophysical contribution to the elucidation of underground structure. Like prospecting by gravity, it began to be used just after the first World War, and the original objective was the same—the discovery of salt domes in Mid-Europe and America. In point of time the refraction method described earlier was the first to be used successfully. The speed of propagation of seismic tremors in the rock salt of the domes was found to be about twice as great as that in the alluvial overburden, so that the physical conditions were quite favourable. Also, the rate at which operations could be carried out exceeded that attainable with torsion-balance gravity observations—then the only alternative means of investigation. In consequence, the seismic refraction method was responsible, during the first few years, for the location of many more salt domes and the related oil reservoirs. More recently, the reflection method has been preferred, on account of the more precise information it is capable of giving as to the shape of underground structure, and because the difficulties of interpreting the records, which I mentioned earlier, have been to a large extent overcome. But I ought to say, especially as the matter comes so closely within my personal knowledge, that the refraction seismic method is still the only one of proved utility in South-West Iran. There, taking advantage of the higher seismic velocity in the buried limestone with reference to that in the overburden, much has been and still continues to be done by means of refraction to delineate the limestone structure and locate the great oil-bearing anticlines described earlier.

The reflection seismic method, in regions amenable to its use, has certain other advantages. The distances which the earth tremors have to traverse are not nearly so great. A tremor starts from the surface explosion and proceeds nearly vertically downwards to reflecting rock bed and back again, whereas in refraction work horizontal distances up to as much as a dozen miles or more are also involved. Consequently, much smaller amounts of explosive are required when reflection is employed—a matter of a few pounds as compared with, perhaps, two tons. Also the process of surveying with the necessary

accuracy the positions of shot points and points of observation is relatively easier, especially in hitherto virgin territory which, more often than not, has to be prospected. These cumulative advantages have led to emphasis being laid in practice on the reflection method, and it may be said generally that nowadays this is the one tried first in attacking new problems. The more elaborate refraction method is in the main regarded as a stand-by for use in cases where, owing to certain surface conditions, usually a very hard bed of rock at shallow depth, no observable reflections from more deeply seated structures can be obtained.

For both applications of the seismic method, the principal part of the necessary equipment is the recording seismometer, that is, a device capable of responding to feeble earth tremors, and a camera for making photographically a continuous record of this response after considerable, often great, amplification. For we are concerned, in practice, with earth movements often less than one ten-thousandth of an inch. There are many types of seismometer employed—too many for any detailed description on this occasion. The principle of all of them is the same, and, curiously enough, the instruments have a close resemblance to gravimeters. A heavy mass is supported by a suitable spring in a framework rigidly attached to the earth. The frame therefore moves as the earth does, but the mass does not at once respond owing to its inertia. Relative displacement between mass and frame thus occurs, and it is this that is magnified and recorded photographically on moving paper or film in the recording camera. When first brought into use the seismometers were mainly mechanical in operation, magnification being obtained on lever principles, followed, of course, by optical magnification in the recording system. But now the instruments universally employ the principle of electromagnetic induction. The earth movements give rise to induced currents in coils of wire suitably disposed with respect to magnets, and these currents, after amplification by well known methods, actuate small reflecting galvanometers. These, in turn, make the photographic traces in the camera. It will be obvious that this method has the great advantage that it makes it possible to obtain on one and the same record the traces, or seismograms as they are called, derived from a considerable number of seismometers placed at different points on the ground and responding to one and the same explosion.

As regards the initiation of the seismic tremors, it would be very wasteful to detonate the charge of explosive actually on the surface of the ground, for then a large proportion of the energy is imparted uselessly to the air. It is therefore customary to fire the charges in

holes drilled to varying depths up to 100 feet or so, tamping them down well so that most of the energy goes into the earth as desired. The instant at which the explosion occurs has also to be recorded on the seismogram being made at the observation point some distance away. This is usually achieved by causing the detonation to trigger an electrical signal which is transmitted without appreciable delay by radio to the recording system. In the camera itself a timing device is incorporated which marks the moving paper, i.e. the seismogram, at equal intervals of time of one tenth, or sometimes one hundredth of a second. Thus, the times of transit of the earth tremors can be measured with a high degree of accuracy, and it is from these, as we have seen, that deductions can be made as to the geological structure below the earth's surface.

When one reckons up all the equipment required—the drilling rig, the gelignite, the seismometers, the recorder, and the wireless outfit—and the personnel required to operate it, usually some eight technically qualified men, as well as numerous labourers, seismic prospecting is seen to be a quite elaborate affair. For the same reasons it is expensive, too, as may be judged by the fact that an operating party costs several thousand pounds per month. Yet many such parties are at work on potential oil fields all over the world, and it is now quite unusual for drilling for oil production to be undertaken without first obtaining all possible evidence by seismic means of suitable rock structure underground. This is the best tribute there could be to the economic utility of the method.

#### VII.—RECENT DEVELOPMENTS IN ELECTRICAL AND MAGNETIC PROSPECTING.

I mentioned earlier that the electrical and magnetic methods might be applied in a subsidiary manner to the elucidation of the structure of rock beds hidden below the surface. As regards the first, all that can be safely said in its present early state of development is that there is some evidence, particularly from observations in the south of France, that rock structure at depth can be delineated if this rock itself is a poor conductor electrically as compared with the material composing the overburden. It may be that the future will present wider fields of useful application in the search for oil, but that remains to be proved by further trials.

Interest in the magnetic method has been recently revived by a very remarkable development of an instrumental and operational character. Formerly magnetic surveying had to be done by means of portable magnetometers erected on the ground surface, and much time was

occupied in transportation from point to point. Now we have the so-called aerial, or airborne magnetometer, which is transported by an aeroplane, sometimes within it, but more often towed behind it in a stream-lined casing, and the magnetic anomalies are actually recorded during flight. The magnetometer employed is based on novel principles, which would take too long to describe here, and is a development of one invented during the war and used with considerable success for the detection of submerged submarines—submarines, of course, being highly magnetic bodies. The chief post-war application is taking place in the United States and Canada, the objective being buried ore-bodies of ferromagnetic character, the speed of the operation enabling great tracts of country to be investigated in a short time. There are reasons for believing, too, that the method may play a part, albeit a secondary and indirect one, in the search for oil-bearing structures. The sedimentary rocks composing these structures are not themselves sufficiently magnetic to be detected on that account by means even of the highly sensitive equipment now available. But there is evidence that the deeper igneous rocks of the geological basement, at any rate in some places, are magnetic enough to give measurable indications on or above the earth's surface, owing to the considerable amount of magnetite or other ferromagnetic material disseminated in them. If, therefore, it may be assumed on geological grounds that the same process of rock folding affected both the basement and the overlying sediments, the magnetic location of the former may imply that of the latter. And, even if this is not the case, magnetic surveying may still supply some useful information. For by making observations at different flying heights it is possible sometimes to estimate the depth of the basement, and learn thereby the thickness of sedimentary cover, which has to be very considerable for the survival of an oil reservoir to be likely therein. Thus the magnetic method may help to show what areas are to be preferred for further survey by the other more direct and efficient means which I have described.

#### VIII.—CONCLUSION.

I am sorry to have to end this lecture on a note of regret. Yet I do so because it is one which, perhaps more than any other, may be of special interest to this famous Institute. I refer to the instruments used in geophysical prospecting and the materials required in their construction. Relatively little geophysical equipment has been invented and developed into practical form in this our own country of Britain; nearly all has come from abroad, especially from America.



There is, for example, no British gravimeter of adequate performance available for the work, and most of the seismic equipment has to be acquired from the United States. I do not believe that our young physicists and engineers lack the ingenuity requisite to compete successfully in this matter. In my view what has most hindered progress has been the unavailability of the special materials required, and the means of fashioning them into the desired form. In both gravimeters and seismometers the most essential component is the metal of which the spring is made. It has to be, as I have already emphasized, as nearly as possible constant in its physical properties, and there is still room for considerable improvement in this respect. I would like, therefore, to see close consultation between metallurgists and geophysicists established with this end in view, and I entertain some hopes that what I have just said will prove a stimulus to such co-operation.

I have tried in this lecture to give a balanced account of the practice and possibilities of prospecting by physical methods. I am conscious of its inadequacy and fear that it may have been dull. Among other things I may have given the impression that geophysical investigations have achieved greater results than they have in fact done. If so, I would wish to correct it by stating frankly that there have been many cases of failure. Even when several methods are used in combination, as is frequently the practice with a view to securing corroborative evidence, some of the more complicated problems have refused to yield to the attack. Experience over years of practice, however, shows, on balance, that the work done has been economically profitable. American authors in oil journals discuss this matter from time to time statistically by comparing the numbers of productive oil fields found with and without geophysical assistance, and the ratio is always much in favour of the former and becomes increasingly so. Moreover, my own belief is that at least some of the methods here described may find useful application in the search for minerals other than oil, when the call for assistance in prospecting comes with sufficient urgency, backed, of course, by preparedness to spend not small amounts of money on the work.

As to the dullness of presentation, I can but hope that it may have seemed less to you than it has done to me, for whom the spark of novelty has faded somewhat, owing to writing and speaking so often on the same subject.

OBSERVATIONS ON THE ANNEALING 1137  
CHARACTERISTICS OF AN ALUMINIUM-  
COPPER-MAGNESIUM ALLOY.\*

By MAURICE COOK,† D.Sc., Ph.D., F.I.M., MEMBER OF COUNCIL, and  
T. LL. RICHARDS,‡ B.Sc., Ph.D., F.I.M., MEMBER.

## SYNOPSIS.

Isochronal annealing curves of heat-treatable alloys of the aluminium-copper-magnesium type show, after a slight initial hardening with increasing temperature, softening in two distinct stages, followed by an increase in hardness. A study of the influence of rolling and annealing conditions has revealed that (a) the initial hardening is associated with age-hardening, and (b) the two softening stages are accompanied by two structural changes, corresponding to recovery and recrystallization, in direct confirmation of the authors' view that softening on annealing is a two-stage process. The final increase in hardening is due to solution of copper and magnesium to a degree of supersaturation which increases with the annealing temperature.

This type of annealing curve characterizes material in the supersaturated or age-hardenable condition, but the curve for the alloy in the non-ageing condition, obtained by recourse to recovery or non-recrystallizing anneals between successive stages of cold rolling, shows a lowering of the recrystallization temperature and no initial hardening.

## I.—INTRODUCTION.

THE behaviour on cold rolling and annealing of alloys which can be hardened by thermal treatments, that is, temper-hardenable or age-hardenable alloys, is dependent, like that of non-heat-treatable alloys, on several factors, but, in addition, it is complicated by the structural condition of the alloy which, in turn, is determined by its thermal history. The form and features of annealing curves of alloys of this type can, therefore, only be correctly interpreted after the influence of the various factors involved has been separately assessed.

The observations recorded in the present paper were made in the course of a detailed study of the cold-working and annealing characteristics of a well known type of commercial heat-treatable aluminium alloy, and the results not only serve to explain the salient and typical features of annealing curves of an alloy of this kind, but also add to available evidence on the processes of recovery and recrystallization.

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The material used was all from the same original casting, and stock at a thickness of 1 in. was hot rolled from a 5-in.-thick extruded slab. For the various experiments, material from this stock was annealed for  $2\frac{1}{2}$  hr. at  $380^{\circ}\text{C}$ . and air cooled, before cold rolling. The composition of the alloy was: copper 4.01, magnesium 0.68, manganese 0.55, silicon 0.36; iron 0.38%, traces of nickel, chromium, titanium, lead, tin, and zinc, remainder aluminium.

The experimental work consisted essentially of hardness measurements and structural observations by X-ray and microscopic methods on materials rolled and annealed under a variety of conditions. Typical hardness and X-ray data resulting from the experiments are reproduced, but no photomicrographs are included, since results obtained by the X-ray methods were more revealing and conclusive.

## II.—ANNEALING CHARACTERISTICS OF STRIP COLD ROLLED FROM ANNEALED HOT-ROLLED STOCK WITHOUT INTERMEDIATE ANNEALING.

Four pieces of the annealed 1 in. stock were cold rolled, without any intermediate annealing, with reductions of 25, 44, 68, and 90% in thickness. Normal isochronal annealing curves for these materials, which are referred to as *A*, *B*, *C*, and *D*, respectively, are shown in Fig. 1. They were obtained by measuring the diamond pyramid hardness of samples annealed for 90 min. at temperatures ranging from  $20^{\circ}$  to  $500^{\circ}\text{C}$ . in an air-atmosphere furnace, followed by quenching in water at room temperature. The structural effects associated with changes in hardness were studied by X-ray back-reflection photographs, using cobalt unfiltered radiation, and also by micro-examination.

As all four curves in Fig. 1 show similar features, only one curve need be described, for example, that of strip *B*, cold rolled with a reduction of 44%. Typical X-ray patterns of strip *B* are reproduced in Figs. 2–9 (Plate XLIV). The annealing curve shows that the hardness after annealing increases with annealing temperature in the range  $20^{\circ}$ – $160^{\circ}\text{C}$ . The X-ray diffraction patterns, Figs. 2 and 3, indicate that the crystal lattice remains distorted after the material has been heated in this temperature range for 90 min., for the diffraction rings remain diffuse.

In the temperature range  $160^{\circ}$ – $250^{\circ}\text{C}$ ., there is a rapid fall in hardness, which is associated with an increase in definition of the X-ray diffraction rings, as shown in Figs. 4 and 5, but the Debye-Scherrer rings are still quite continuous, and diffraction spots of a size which can be photographically resolved are absent. In this region, removal of lattice distortion or recovery occurs without recrystallization. From  $250^{\circ}$  to  $290^{\circ}\text{C}$ . there is a more gradual decrease in hardness, accompanied by a

further slight increase in the definition of the diffraction rings. In the next temperature range, 300°–340° C., there is a second rapid fall in hardness, and the appearance of sharp discrete spots in the diffraction patterns indicates that recrystallization is just beginning at 300° C. (Fig. 6), that it is more advanced after heating at 310° C. (Fig. 7), and that it is complete after heating at 340° C. (Fig. 8). Finally, the

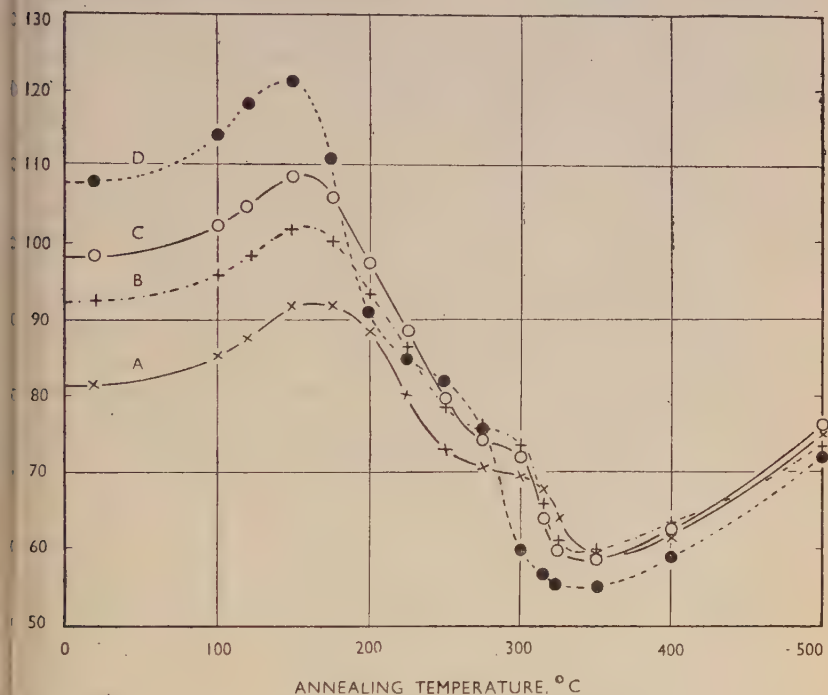


FIG. 1.—Normal Isochronal Annealing Curves for Strip Cold-Rolled from Annealed Hot-Rolled Stock without Intermediate Annealing.

hardness increases with annealing temperature in the range 340°–500° C., but the diffraction pattern, Fig. 9, indicates no significant change in crystal structure.

The diameters of the diffraction rings in Fig. 9 of sample *B* annealed at 500° C., however, are clearly less than those of the corresponding rings in Fig. 8 of the same strip heated at 340° C. This represents a diminution in lattice parameter with increase in temperature of annealing, which is the net result of copper and magnesium being taken into solid solution, which, in turn, accounts for the final increase in hardness.



Specimens quenched from temperatures above  $340^{\circ}$  C. are in a supersaturated condition and thus age-harden at room temperature. The age-hardening, which is appreciable in specimens annealed at  $350^{\circ}$  C., and becomes more pronounced with increasing temperature of anneal, has no visible effect on the grain structure.

In the micro-examination of incompletely annealed specimens, considerable difficulty was encountered in revealing structural features clearly. It would seem, however, that there was no change which could be associated with recovery, and the first significant change in micro-structure that could be observed was actual recrystallization. In this respect, the metallographic observations were entirely in accord with those of X-ray diffraction techniques, the first sign of recrystallization being observed in sample *B* annealed for 90 min. at  $300^{\circ}$  C. and complete recrystallization in sample *B* annealed at  $340^{\circ}$  C. No further significant change in structure was observed in samples heated at temperatures above that at which recrystallization was complete.

Comparison of the four curves *A*, *B*, *C*, and *D*, Fig. 1, indicates that the temperature at which the initial hardening is a maximum decreases with increasing rolling reduction, but the magnitude of the increase in hardness does not appear to be directly related to the magnitude of the rolling reduction. Increased rolling reduction lowers both the temperature range of recovery and recrystallization progressively, and the most heavily cold-rolled material yields the softest annealed product, and the most lightly rolled, the hardest.

An initial increase in hardness of cold-rolled materials on subsequent heating at progressively increasing temperatures is quite usual. It is generally, if it occurs at all, very small for pure metals <sup>1</sup> and greater for solid-solution alloys, <sup>2,3,4</sup> the magnitude of the increase for any particular material usually increasing with the degree of cold rolling. The effect may be akin to strain-ageing in mild steel, which has been explained by Cottrell <sup>5</sup> as being due to a diffusion of solute atoms to regions of maximum lattice distortion, and this view is confirmed by the results of further tests which are discussed later.

The two softening stages observed in the annealing curves of the cold-rolled heat-treatable aluminium alloy used in this investigation are associated with two distinct structural changes, namely removal of lattice distortion or recovery, and generation of new crystals or recrystallization. These observations thus provide confirmation of the conception that softening of cold-worked metals on annealing occurs in two stages, as the authors, in the course of an earlier investigation, <sup>6</sup> showed by an analysis of data on the softening rates of heavily cold-rolled H.C. copper strip.

### III.—INFLUENCE OF COLD ROLLING WITH INTERMEDIATE ANNEALING.

A number of samples of the annealed 1 in. hot-rolled stock were cold rolled to a final thickness of 0.1 in. in eight, four, and two successive reductions of 25, 44, and 68%, respectively, with intermediate annealing. From the observations made in the series of tests described in the foregoing Section, it was possible to select two conditions for which all three lots of material could be annealed at all intermediate gauges so as to obtain (1) maximum softening without any recrystallization and (2) complete recrystallization and softening to minimum hardness. The first of these conditions was realized by heating the alloy for 90 min. at the temperature necessary for complete recovery ( $280^{\circ}\text{C}.$ ), and quenching, that is, at a temperature corresponding to the end of the first softening stage shown by the curves in Fig. 1. In order to ensure that the complete softening necessary for the second condition was realized, and to reduce the rate and magnitude of subsequent ageing, samples were heated at  $420^{\circ}\text{C}.$  for 90 min., slowly cooled to  $360^{\circ}\text{C}.$ , and quenched.

All the samples were indexed by a letter and a number, *A*, *B*, or *C* indicating that the magnitude of the cold-rolling reduction at each of the eight, four, or two stages of cold rolling from 1 in. was 25, 44, or 68%, respectively, and the 1 or 2 indicating that the intermediate annealing condition was (1) non-recrystallizing or (2) completely recrystallizing, respectively. Thus, for example, *B*1 was a strip cold rolled from annealed 1 in. hot-rolled stock in four stages each of 44% reduction in thickness with intermediate non-recrystallizing anneal of 90 min. duration at  $280^{\circ}\text{C}.$  The final condition of any particular sample is not specified by the indexing scheme but is clearly defined in the text.

#### 1. *Work-Hardening and Ageing.*

The hardness values of the various samples at the intermediate gauges, both immediately after cold rolling and after subsequent annealing, are shown in Fig. 10. The full lines in this Figure connect hardness values for strips *A*1, *B*1, and *C*1 cold rolled with intermediate non-recrystallizing anneals, and the broken lines the hardness values for strips *A*2, *B*2, and *C*2 cold rolled with intermediate recrystallizing anneals. Each curve is a series of inclines, representing the rise in hardness as a result of cold rolling, and verticals, representing the fall in hardness on annealing. The first rolling stage in each of the three schemes was identical for each pair of strips, but in subsequent stages the different annealing conditions resulted in different hardness both immediately after cold rolling and after annealing. The hardness

of cold-rolled strip immediately after a non-recrystallizing anneal is greater than after a fully recrystallizing anneal, but on subsequent cold

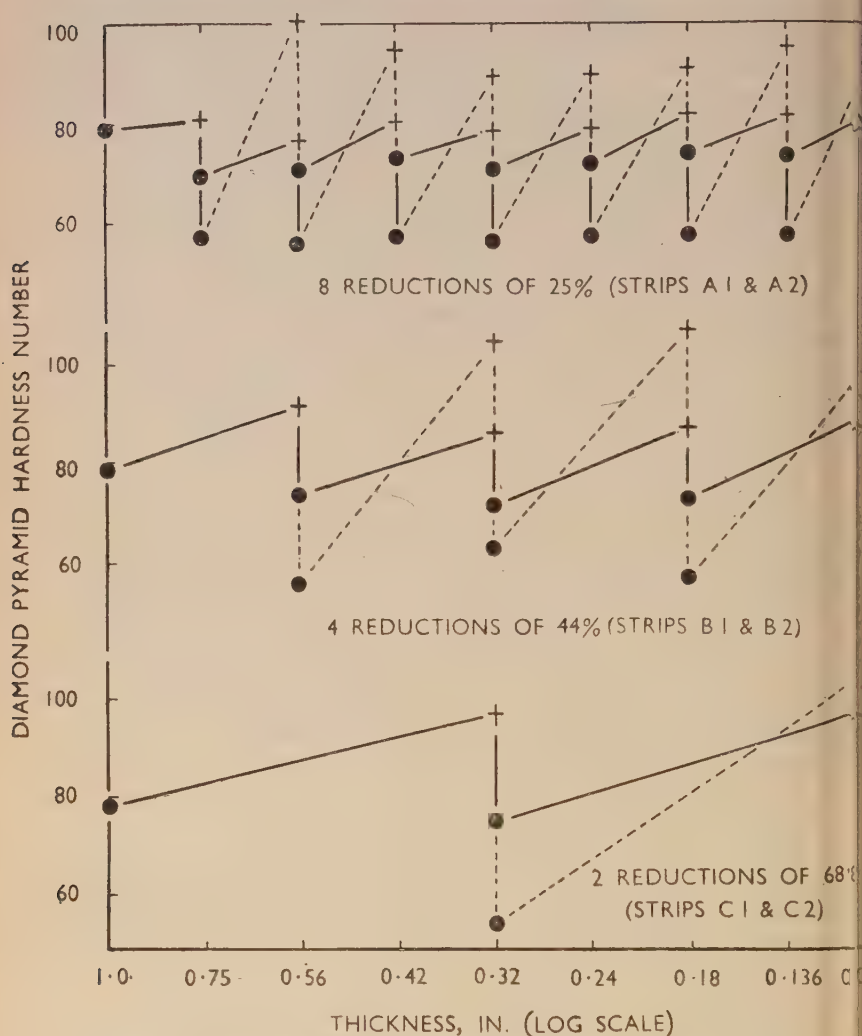


FIG. 10.—Hardness at Various Stages in Cold Rolling 1 in. Slab to 0.1 in.  
Solid lines: intermediate annealing at 280° C.  
Broken lines: intermediate annealing at 420° C. with slow cooling to 360° C.

rolling with any particular reduction in thickness, the fully recrystallized material, as shown in Fig. 10, is the harder.

FIG. 2. As rolled.  
FIG. 3. 160° C.  
FIG. 4. 200° C.  
FIG. 5. 250° C.

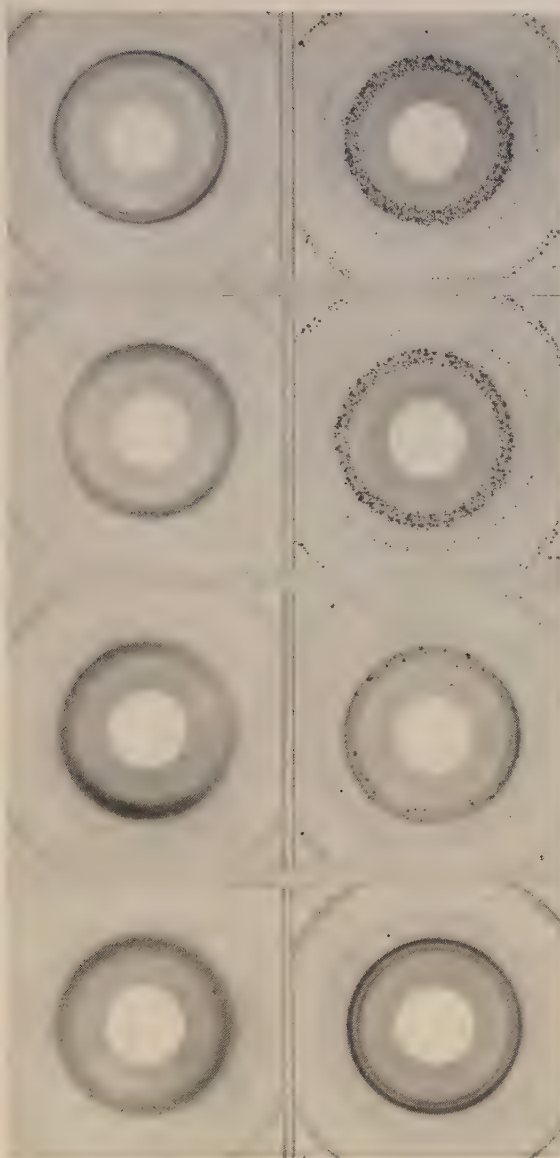


FIG. 9.  
500° C.

FIG. 8.  
340° C.

FIG. 7.  
310° C.

FIG. 6.  
300° C.

X-Ray Back-Reflection Photographs (Cobalt Radiation) of Cold-Rolled Strip Annealed at the Temperature Indicated.





FIG. 11.—Non-crystallizing intermediate anneal      FIG. 12.—Recrystallizing intermediate anneals

X-Ray Back-Reflection Photographs (Copper Radiation) of Cold-Rolled Strip after Rolling from 1 in. to 0.1 in. in Four Stages.

FIG. 15.      FIG. 16.      FIG. 17.      FIG. 18.

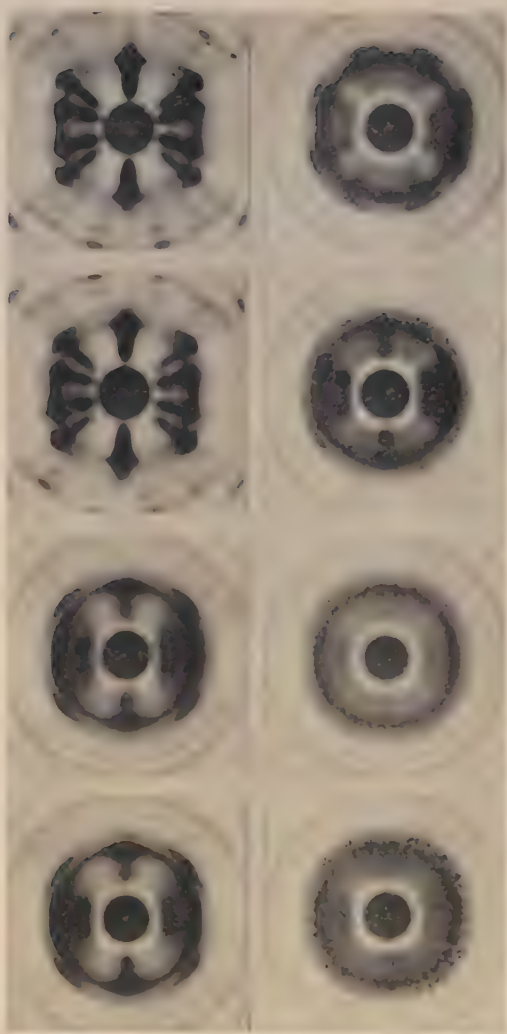


FIG. 19.      FIG. 20.      FIG. 21.      FIG. 22.

Final Reduction, % 25      44      68      90  
X-Ray Transmission Photographs (Molybdenum Radiation) After Varying Single Rolling Reduction  
Rolling Direction. (a) As rolled. (b) Heat-treated at 550° C.

The difference in behaviour during subsequent cold rolling between strip processed with intermediate non-recrystallizing anneals and that with fully recrystallizing anneals is also clearly revealed by X-ray diffraction patterns. As can be seen in Figs. 11 and 12 (Plate XLV), from a relative definition of the patterns of the 0.1 in. cold-rolled samples *B1* and *B2* there is, in the former, which was cold rolled after non-recrystallizing anneals, a lesser degree of lattice distortion, corresponding to a lesser work-hardening of the material, than there is in the latter, which was cold rolled after a fully recrystallizing anneal.

In order to examine in more detail the relative work-hardening and ageing characteristics of the alloy after non-recrystallizing and fully recrystallizing anneals, samples *A1* and *A2* after final rolling to 0.1 in. were annealed respectively at 280° C., and at 420° C. with slow cooling to 1360° C., quenched, and rolled immediately afterwards with various reductions in thickness of up to 70%, hardness tests being carried out immediately after rolling and after ageing for 50 days at room temperature.

The results of these tests, which are plotted in Fig. 13, show that *A2* (curve *b*) subjected to the fully recrystallizing anneal at 420° C., while initially softer than the non-recrystallized sample *A1*, work-hardens much more rapidly, and after a reduction of only about 5% the two are of equal hardness. The more rapid hardening of *A2* continues to a reduction of about 15%, but with increasing degree of cold work the two materials harden at about the same rate.

Strip *A1* is practically in a non-ageing condition and, therefore, the results of hardness tests immediately after rolling or 50 days afterwards both fall substantially on one curve *a* in Fig. 13. Strip *A2*, however, ages some 14 hardness numbers in the unrolled condition, and the extent of ageing decreases as the rolling reduction is increased up to about 15%. Thereafter, the extent of ageing is practically constant at about 2 or 3 points. The work-hardening curve of this material as determined immediately after rolling is shown in curve *b* and corresponding hardness determinations on the same material after 50 days in curve *c* of Fig. 13.

Over the range of reductions in excess of about 15–20%, the curve *a* is roughly parallel to the two curves *b* and *c*, the distance between them, expressed as hardness numbers, being approximately equal to the amount by which *A2* ages in the soft condition, from which it would seem that the difference between curves *a* and *c* is ascribable to the ageing effects to which the *A2* material is susceptible. As noted by Gayler,<sup>7</sup> cold working accelerates the rate of ageing, and, as can be seen from an examination of the first portions of the curves *b* and *c*, the extent of

ageing that can occur, subsequent to cold working, diminishes up to reductions of the order of 15%.

The hardness values of the variously treated samples are plotted in Fig. 13 against the logarithm of the strip thickness, a scale which is

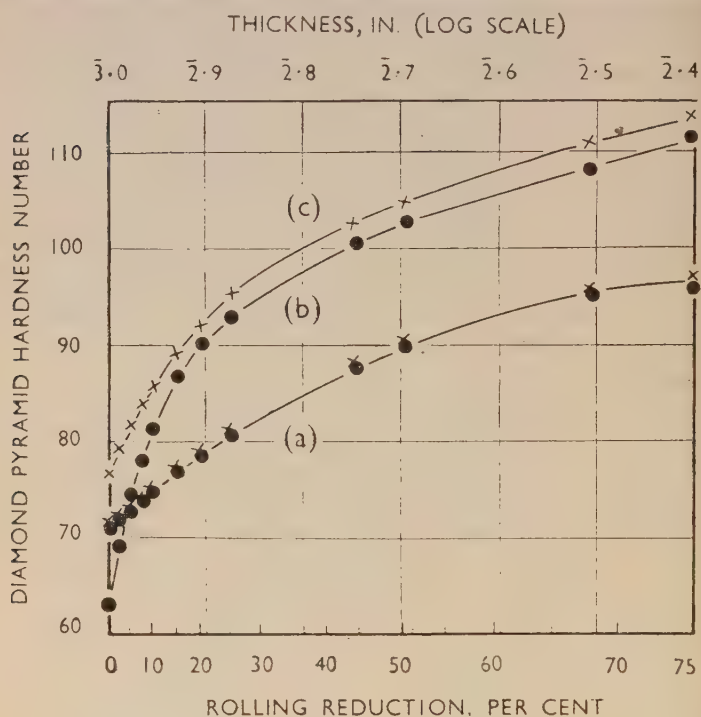


FIG. 13.—Work-Hardening and Ageing of 0.1 in. Strip.

- (a) Strip A1 annealed at 280° C. and cold rolled; tested (●—●) immediately after rolling and (×—×) after ageing at room temperature for 50 days.  
 (b) Strip A2 annealed at 420° C., slowly cooled to 360° C., and cold rolled; tested immediately after rolling.  
 (c) As (b), but tested after ageing at room temperature for 50 days.

proportional to the true strain or deformation of the material by cold rolling. The work-hardening curve of A2 (b) shows a rapid initial increase in hardness for reductions in thickness up to about 15%, followed by work-hardening at a much lower rate at reductions in excess of this amount. Curves of this type are quite typical for metals and alloys, and in the case of 70 : 30 brass it has been shown by the authors<sup>4</sup> that the corresponding change in the rate of work-hardening which

occurs at a reduction in thickness by cold rolling of about 40% is associated with a change in the mechanism of deformation from crystallographic slip to crystal break-up.

It may well be that the change of rate in work-hardening shown by curves of a kind illustrated by curve *b* in Fig. 13 corresponds to the position on ordinary tensile-test stress-strain curves where uniform elongation ceases and necking commences, as evidence both from this alloy and 70:30 brass suggests. The uniform elongation of this aluminium alloy in strip form, as measured in ordinary tensile testing, has a value a little less than the 20-22% which is normally recorded as the total % elongation on a 2 in. gauge-length for the material in the unworked condition, provided it is fully recrystallized. A reduction in thickness by rolling of about 15% is equivalent to an elongation of 18%, which approximates to the uniform elongation of the alloy in tensile testing. In 70:30 brass, the position of the change in rate of work-hardening which occurs at a reduction of approximately 40%, corresponds to an elongation of about 66%, which is of the same order as the uniform elongation of this alloy in the annealed condition.

It is significant also to note that the change in rate of work-hardening of the fully recrystallized aluminium-copper-magnesium alloy occurs at about the same rolling reduction as that at which increase in the work-hardening, associated with ageing, is virtually complete.

#### *Influence of Variation in Intermediate Annealing Conditions on Annealing Characteristics.*

Normal isochronal annealing curves were established for the 0.1 in. strips *A1*, *B1*, and *C1*, and *A2*, *B2*, and *C2*, the first three being cold rolled from annealed 1 in. hot-rolled stock with eight, four, and two reductions of 25, 44, and 68%, respectively, with intermediate non-recrystallizing anneals, and the other three with similar reductions but with fully recrystallizing intermediate anneals. The various samples were annealed for 90 min. at temperatures up to 500° C. and hardness tests made immediately after quenching into water at room temperature. Some of these curves, namely those of *A1*, *B1*, *C1*, and *B2*, are reproduced in Fig. 14. Those of *A2* and *C2* have been omitted to avoid overlapping, but they were similar in character to that of *B2* and showed the effect of increasing the magnitude of the final rolling reduction much in the same way as already described for the curves in Fig. 1. The curve for strip *D*, cold rolled directly from annealed 1 in. hot-rolled stock to a final thickness of 0.1 in., already reproduced in Fig. 1, is included in Fig. 14 for the purpose of comparison.

Curves for *B2* and *D* show all the main characteristics of the annealing



curves reproduced in Fig. 1, that is, an initial hardening, followed by softening in two steps, and a final increase in hardness with increasing temperature of annealing above that corresponding to minimum hardness. X-ray examination again confirmed that the first step in softening was associated with removal of lattice distortion or recovery and the second step with recrystallization. The curves for these two

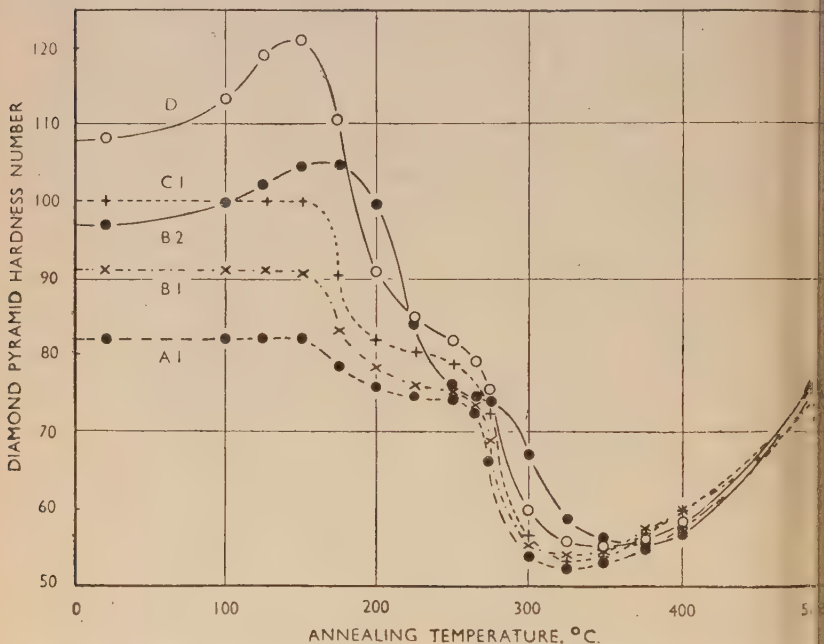


FIG. 14.—Normal Isochronal Annealing Curves Showing Influence of Variation in Intermediate Annealing Conditions on Annealing Characteristics.

samples also show the usual lowering of softening temperature with increasing amount of cold rolling.

The annealing curves of specimens A1, B1, and C1, rolled with intermediate non-recrystallizing anneals, however, show some significant differences. In the first place there was no indication of any hardening before the first softening, the hardness remaining substantially unaltered up to a temperature of 150° C. The softening of all three strips occurred in two stages which were, because of the absence of any initial hardening, more clearly defined than the two softening stages in annealing curves of strip cold rolled after fully recrystallizing anneals. The magnitude of initial softening, which was again associated with a sharpening of the

Debye-Scherrer rings without the appearance of discrete diffraction spots, was roughly proportional to the degree of cold working. Distinguishable recrystallization was observable in all three strips after annealing at a temperature of 275° C., and after annealing at about 220° C. they were all fully soft.

The temperature of the second softening stage in the annealing curves for each of the strips *A1*, *B1*, and *C1*, which were cold rolled with a total reduction in thickness of 90% in two, four, and eight stages, respectively, with intermediate non-recrystallizing anneals, was in all cases lower than the corresponding temperature for strip *D*, which was reduced 90% in thickness without any intermediate annealing. Contrary to what might be expected, the recrystallization temperature is slightly lowered rather than raised by increasing the number of intermediate non-recrystallizing anneals, in spite of the fact that the magnitude of the final cold-rolling reduction and hardness of the strip after rolling is thereby decreased.

As already mentioned in the discussion of the annealing curves in Fig. 1, the final increase in hardness is probably due to copper and magnesium being taken into solid solution. That the aluminium-copper-magnesium alloy studied is in a supersaturated condition when quenched from temperatures above about 360° C. is indicated by the fact that in this state it age-hardens at room temperature. Material annealed at, and quenched from, temperatures below that at which recrystallization occurs exhibits no subsequent ageing. The initial hardening which is observed only in annealing-curves of strip cold rolled after recrystallizing anneals would thus appear to be associated with ageing.

On heating cold-rolled strip at 280° C. for 90 min. the material approaches its equilibrium condition for that temperature and it becomes virtually non-ageing. With repeated thermal treatments of this kind, the complete equilibrium state, with little copper in solid solution, is more closely approached, which explains the observed lowering of the recrystallization temperature with increasing number of intermediate non-recrystallizing anneals.

The fact that in annealing-curves of material cold rolled after both non-recrystallizing or recrystallizing anneals softening occurs in two steps indicates that the first step is not related to any ageing phenomenon but is associated entirely with the process of recovery.

The magnitude of the fall in hardness occurring in the first softening diminishes with increasing number of non-recrystallizing anneals, while the fall in hardness in the second stage is but little affected. This diminution in the extent of softening at the recovery stage is mainly due

to a lower initial hardness resulting from a decrease in the magnitude of final rolling reduction. Sample *A1*, however, which had eight non-recrystallizing intermediate anneals, is more nearly in equilibrium and has less of the solute elements in solid solution than sample *B1* which had four, and still less than sample *C1* which had only two non-recrystallizing anneals. Some of the diminution in the extent of initial softening of the three samples, therefore, is due to a difference in the rate and extent of work-hardening of the strips arising from their slightly different equilibrium conditions.

#### IV.—STRUCTURE AFTER COLD ROLLING, RECOVERY, AND SOLUTION HEAT-TREATMENT.

The preferred orientation of crystals developed in the various 0.1 in.-thick samples of strip in the cold-rolled condition, after a non-recrystallizing anneal at 280° C., and complete recrystallization on solution heat-treatment, was studied by X-ray transmission photographs taken with unfiltered molybdenum radiation. A series of typical patterns is reproduced in Figs. 15–22 (Plate XLV).

In the cold-rolled strip, the degree of preferred orientation increases with the magnitude of the final cold-rolling reduction, when this is

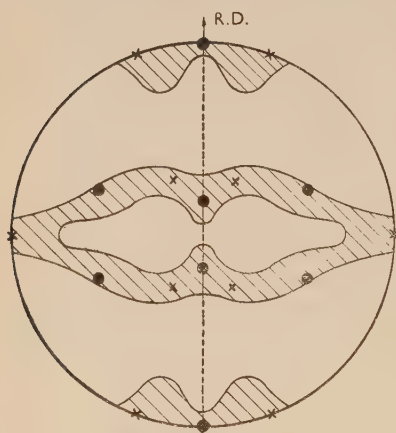


FIG. 23.—Pole Figure of Octahedral or (111) Planes in Strip *D* Cold Rolled 90%.  
Plane of figure parallel to strip surface.

× (110) [112] texture.  
● (112) [111] texture.

lessor proportion of a structure orientated with a {112} plane parallel to the strip surface and a  $\langle 111 \rangle$  axis parallel to the rolling direction. The

effected either on the annealed hot-rolled blank or after a recrystallizing intermediate anneal. A full pole figure showing the distribution of the close-packed (111) or octahedral planes of the face-centred cubic lattice of the aluminium-rich matrix is reproduced in Fig. 23. From this Figure it is evident that the structure of the heavily cold-rolled strip is composed mainly of the twin texture which is common to most cold-rolled metals having a face-centred cubic structure, namely that with the (110) plane parallel to the strip surface and either the  $[\bar{1}12]$  or  $[1\bar{1}2]$  axis parallel to the rolling direction, together with a



latter is also a twin texture, the two components having a common  $\langle 111 \rangle$  axis in the rolling direction. The twin orientations of the secondary texture might be regarded as stable orientations intermediate between those of the main twin textures.

Examination of the various samples before and after intermediate non-recrystallizing anneals revealed that recovery occurred on such annealing by removal of lattice distortion without change in crystal orientation. Subsequent cold rolling increased the preferred orientation to the same degree as that in strip cold rolled by the same total extent without intermediate anneal. Thus, the preferred orientation in strip A1, cold rolled with eight equal reductions of 25% with intermediate non-recrystallizing anneals, was developed to the same degree as that in strip D cold rolled to the final thickness of 0.1 in. without any intermediate anneal.

The structure of the final 0.1 in.-thick strip in the solution heat-treated condition is also illustrated by the series of X-ray transmission photographs reproduced in Plate XLV. The orientation of crystals was almost random in A2 cold rolled with a final reduction of 25% after a recrystallizing anneal (Fig. 19), but with increasing final cold-rolling reduction there was appreciable preferred orientation after solution heat-treatment. With cold-rolling reductions of 44 and 68% before solution heat-treatment (Figs. 20 and 21, respectively), the preferred orientation was of a similar type to that in the cold-rolled strip, but with a reduction of 90% (Fig. 22) a preferred orientation of a new type made its appearance on heat-treatment. The pole figure representing the distribution of the octahedral planes in strip D cold rolled with a final reduction of 90% and heat-treated is reproduced in Fig. 24, but the

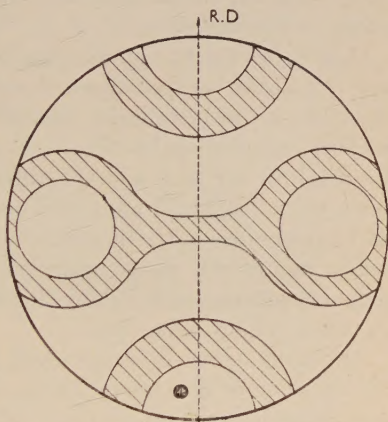


FIG. 24.—Pole Figure of Octahedral or (111) Planes in Strip D Cold Rolled 90%, after solution heat-treatment. Plane of figure parallel to strip surface.

recrystallized texture, unlike the rolled texture, cannot be defined by single crystallographic indices. Comparison of the pole figure of the heat-treated strip (Fig. 24) with that of the same strip in the cold-rolled condition (Fig. 23) indicates that recrystallization on solution heat-treatment, in contrast with recovery on annealing



at temperatures below  $280^{\circ}$  C., occurs with substantial atomic rearrangement.

#### V.—SUMMARY.

Annealing curves of a heat-treatable aluminium-copper-magnesium alloy cold rolled from annealed 1-in.-thick hot-rolled stock with reductions in thickness ranging from 15 to 90% all show a marked hardening before softening, which occurs in two well defined stages, and a final increase in hardness with increasing temperature above that required to obtain minimum hardness. The two successive steps in softening are due to the removal of lattice distortion or recovery, and to actual recrystallization respectively. These observations provide additional evidence that softening of cold-worked metals on annealing is a two-stage process, as was concluded in a previous investigation on the rate of softening of heavily cold-rolled pure copper.<sup>6</sup>

The final increase in hardness with increasing annealing temperature above that corresponding to minimum hardness, shown by all the annealing curves, is a result of copper and magnesium being taken into solution. As in other metals, increase in the magnitude of the cold-rolling reduction of the fully recrystallized alloy lowers the recrystallization temperature.

Strip subjected to non-recrystallizing anneals does not age-harden since it is not in a supersaturated state, but it is harder than material subjected to recrystallizing anneals which is supersaturated and, therefore, age-hardenable. On cold rolling, the former work-hardens at a much slower rate, and the difference in hardness after any given rolling reduction would appear to be equal to the extent to which the latter age-hardens in the unworked state. Recrystallized material age-hardens appreciably in the unworked condition, but the extent of age-hardening subsequent to cold rolling decreases to a constant value with increasing rolling reductions.

Annealing curves of strips which have been cold rolled with either recrystallizing or non-recrystallizing intermediate anneals show all the main features common to those of strip cold rolled from annealed hot-rolled stock, except that there is no increase in hardness before this initial softening in the curves of strip subjected to intermediate non-recrystallizing anneals. It would, therefore, seem that the initial hardening observed in the annealing curves of strip is directly associated with ageing.

By increasing the number of non-recrystallizing intermediate anneals, complete equilibrium condition in the material is progressively approached and the recrystallization temperature lowered.

Cold rolling results in a progressive increase in the degree of preferred orientation of crystals, which is unaffected by subsequent non-recrystallizing anneals, that is heating under conditions which effect recovery only. Strip cold rolled with a sequence of small reductions and intermediate non-recrystallizing anneals to a total reduction in thickness of 90% shows the same degree of preferred orientation as strip cold rolled with a single reduction of 90% without intermediate annealing.

On solution heat-treatment at 500° C., strip cold rolled with a final reduction of 25% after a recrystallizing anneal, recrystallizes with a completely random orientation of crystals, whereas material rolled with final reductions of 44 and 88% recrystallizes with a preferred orientation similar to that present in the strip after cold rolling. Strip processed with a rolling reduction of 90% without intermediate annealing, or with a total reduction of 90% and intermediate non-recrystallizing annealing, shows, after solution heat-treatment, a preferred orientation different in character from that in strip in the rolled condition, which indicates complete atomic re-arrangement, a fact clearly distinguishing recovery from recrystallization.

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